

The bioliq[®] Entrained-Flow Gasifier – A Model for the German Energiewende

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Abstract


The bioliq[®] process was developed at the Karlsruhe Institute of Technology (KIT) for the production of synthetic fuels from dry biomass residues. Biofuels of high quality are produced sustainably in various process steps. This multistage process not only considers the necessity for decentralized supply of the biomass, but also the necessity for a large centralized fuel synthesis that benefits from economy of

scale. The entire process chain of pyrolysis, gasification, gas cleaning, and synthesis is operated on a pilot scale at KIT. The high-pressure entrained-flow gasifier converts the biomass, pretreated in a fast pyrolysis step, into a synthesis gas for the production of gasoline in the subsequent synthesis step. The first experimental results from the pilot plant are presented in this paper.

Keywords: Bioliq[®], Biomass, Entrained flow, Gasification

Received: April 16, 2020; accepted: April 27, 2020

DOI: 10.1002/cben.202000006[‡]

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1 Introduction

Reducing greenhouse gases in the atmosphere is a political goal accepted worldwide. The transport sector contributes approx. 20% to the world's CO₂ emissions. CO₂ emission from traffic can be reduced by the operation of electric vehicles, provided that electricity generation is based on renewable energies. However, because of the low storage capacities of electrochemical storage media, this will only be an option for short-distance transport tasks. Long-distance traffic, transport of loads, shipping and, in particular, air traffic will require the use of internal-combustion propulsion systems which use chemical energy sources (fuels) of high energy density. CO₂ emissions from this transport sector can be curbed by chemical energy resources from renewable origins. Two possible main routes to the production of the fuels are: (i) the so-called PtX technologies, which produce chemical energy resources from renewable electricity by way of electrolysis and synthesis, and (ii) the 2nd generation BtL technologies, such as bioliq[®] [1], which produce the chemical energy resources on the basis of biogenic residues by gasification and synthesis as process steps.

High-pressure entrained-flow gasification, the core process of the BtL chain for converting biogenic carbon-free raw materials into fuels, is going to be an important path to satisfying market demand for fuels of high energy density that are neutral with respect to CO₂, in this way making an important contribution to closing the carbon cycle in a future energy system. Suitable biomass residues stem from both agriculture and forestry. The un-

used potential of biogenic residues and waste materials in Germany in 2015 amounted to 448 PJ (of which 141 PJ came from straw, while 218 PJ came from residual forest wood) [2].

The bioliq[®]-BtL process chain, operated on a pilot scale at the Karlsruhe Institute of Technology (KIT) for the production of 2nd-generation fuels from dry biogenic residues, makes an important contribution to the introduction of industrial-scale

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[‡]Updated English version of DOI: <https://doi.org/10.1002/cite.201700086>

BtL process chains, which is going to be an important element on the way to reaching the climate goals referred to above.

2 Gasification Techniques – An Overview

Gasification converts solid, liquid, and gaseous energy resources and fuels into so-called synthesis gas, consisting mainly of carbon monoxide and hydrogen, in a reaction with gaseous media, normally oxygen and water vapor, at high temperatures. In downstream process steps, the synthesis gas is used to synthesize chemicals and liquid or gaseous chemical energy resources, such as fuels, synthetic natural gas, or for electricity generation in gas turbine power plants and integrated gasification combined cycle (IGCC) power plants.

Since the 1920s, various gasification technologies have been developed, especially in Germany, for a variety of feed materials and synthesis gas applications. The systems are subdivided into three technologies: moving-bed, fluidized-bed, and entrained-flow gasification [3]. All gasification technologies represent today's state of the art, but the appropriate technology must be chosen for the respective application. The development of gasification technology can be read in [3, 4], while a database with the technical data of most technical-scale gasification plants is available in [5].

It is reported that approximately 690 gasifiers with a synthesis gas capacity of approximately 120 GWth were operated worldwide in 2014. Coal is by far the most important feed material, contributing approx. 60%. The synthesis gas generated is used mainly to produce chemicals (60%) and liquid fuels (25%). Entrained-flow gasification is the dominant technology worldwide with some 350 systems and a synthesis gas capacity of approx. 80 GWth. Newly built plants are almost exclusively entrained-flow gasifiers, the exceptions being, e.g., fixed-bed gasifiers for coal with high ash content from China and India.

The development of gasification technologies for biogenic feed materials began as late as in the past few decades (after 1980). However, know-how and experience with gasifiers for fossil feed materials can be transferred only to a limited extent as the properties of biogenic feed materials, e.g., low calorific value, high moisture content, and high ash content with low ash fusion temperatures, differ greatly from those of fossil feed materials used on a technical scale. In addition, there is a wide range of variations in the typical properties and compositions of biomasses, which constitutes a major challenge in biomass gasification. A good overview of the biomass gasifiers operated worldwide can be found in [6]. That database indicates that typical biomass gasifiers are operated at much lower fuel throughputs than the technical-scale gasifiers for fossil feed materials. The technology employed in most cases is fixed-bed gasification of wood with capacities in the range of 10–100 kW. There are some fluidized-bed gasifiers with synthesis gas capacities of 100 kW to 20 MW. Entrained-flow gasification so far has been used only on a pilot scale up to approx. 5 MW.

3 The bioliq[®] Concept

A pilot plant for the entire process chain of the bioliq[®] BtL process was built after 2005 and commissioned step by step. It was developed at the KIT with the financial participation of the German Federal Ministry for Food and Agriculture (BMEL) represented by the Technical Agency for Renewable Raw Materials (FNR), the Helmholtz Association of German Research Centers (HGF), and the plant designers and manufacturers responsible for the individual process stages. The gasifier stage (with Air Liquide as the cooperation partner) has been in operation since 2012, the entire process chain since late 2014. Since then, the system has been systematically tested and optimized in the individual process steps.

This concept of decentralized energy concentration to make the transport of biomass over longer distances economically meaningful constitutes the unique selling point of bioliq[®]. The following stages will be located at an industrial site offering the possibility of good coupling of process flows in a process network of energy and materials. The Karlsruhe synthesis fuel is produced in a multistage process (Fig. 1)

- 1) Fast pyrolysis: In the first step, the peripherally sourced biomass is converted into pyrolysis oil and pyrolysis coke by fast pyrolysis at approx. 500 °C. The dry biomass is crushed and mixed with hot, mechanically fluidized sand. The sand is the heat carrier in the twin-screw mixing reactor; there the biomass is pyrolyzed in the absence of air at ambient pressure. In this process, heating – the actual pyrolytic conversion of biomass particles at approx. 500 °C – and condensation of the pyrolysis vapors occur in a matter of seconds. This produces roughly 34% organic condensate (pyrolysis oil), 25% aqueous condensate, and 20% pyrolysis coke. The balance is made up of a non-condensable pyrolysis gas whose heat of combustion can be used to heat the sand or to dry and preheat the feed materials.
- 2) Slurry production: The porous pyrolysis coke is ground finely and suspended in the pyrolysis oil. As pyrolysis oil is not directly used as a liquid fuel, there is no need at this point for expensive processing and cleaning procedures. The weight fraction of coke should be as high as possible (up to 40%), with pumpability being ensured along with storability and safe transportability. The suspension produced, referred to as Biosyncrude[®], has roughly 10 times the energy content by volume of the feed material, thus enabling economical transport over long distances [6].
- 3) High-pressure entrained-flow gasification: The biomass-based oil/coke slurries are transported from the pyrolysis plants to a central entrained-flow gasifier facility and converted into synthesis gas at pressures of up to 80 bar and temperatures above 1200 °C. This achieves almost complete, fast conversion into a tar-free gas. The use of fuels with high ash content is made possible by a cooling screen on which the slag is deposited as a liquid and runs down the reactor wall. The synthesis gas is delivered to the following process stage at high pressure [7].
- 4) Gas cleaning and conditioning: The raw synthesis gas is cleaned and conditioned at a pressure above synthesis pressure. This obviates the need for energy-intensive intercom-

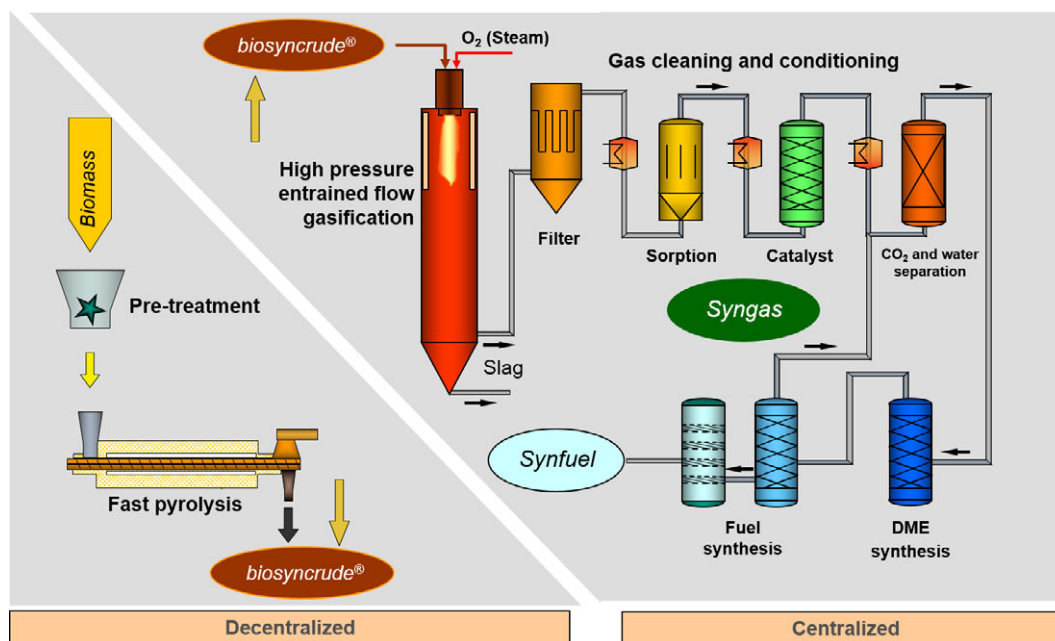


Figure 1. bioliq® process flowsheet.

pression of the cleaned synthesis gas prior to fuel or chemical synthesis. However, the raw synthesis gas must be cleaned of particles, alkaline salts, H_2S , COS , CS_2 , HCl , NH_3 , and HCN to avoid poisoning of the catalysts used in the following synthesis step.

- 5) Fuel synthesis: Gasoline synthesis is achieved in two stages via dimethyl ether (DME) as an intermediate product. DME synthesis is conducted at approx. 250 °C and 55 bar. Afterwards, it is converted into gasoline-grade fuel in the facility at approx. 350 °C and 25 bar [8].

The bioliq® concept is especially suitable for the decentralized sourcing of biomass and its comparatively low energy content. Fast pyrolysis, e.g., of straw, can be carried out in regionally distributed compact facilities with collection areas of up to 50 km. That way, transporting the slurry, whose energy content is condensed, makes sense economically, even over longer distances. Gasification and synthesis are conducted at a few highly integrated locations (chemical plants, refineries) so as to enhance the economic viability of the process chain. The economic viability of the process can be optimized by harmonizing the source and availability of the biomass, the collection area, the number of pyrolysis plants to be set up and the transport distances to the central gas generator. This is a key feature of the bioliq® concept. In addition, this approach offers high flexibility with regard to the fuel suspensions to be used. They can be produced from a variety of feed materials and other liquid and solid feed can be added. In the bioliq® BtL process, 1 t of fuel is produced from approx. 8 t of biomass. Merely by using the residual biomasses referred to above, it is possible in Germany to achieve a share in excess of 5 % of the present fuel consumption.

4 The bioliq® High-Pressure Entrained-Flow Gasifier

The bioliq® entrained-flow gasifier is a key model for converting biogenic energetic raw materials into chemical energy resources and basic feed materials for the chemical industry, with the objective of closing the carbon cycles in future energy systems. It is a research tool for developing entrained-flow gasification technology for industrial implementation.

The design of the bioliq® high-pressure entrained-flow gasifier is based on the referenced Lurgi-MPG™ Technology (multi-purpose gasification) of Air Liquide Global E&C Solutions Germany GmbH, Frankfurt (formerly Lurgi GmbH). The process was originally developed for oil gasification and adapted to the specific needs of gasification of biomass-derived feed materials. Fig. 2 shows the process flowsheet of the pilot gasifier.

The bioliq® entrained-flow gasifier is designed for operating pressures of 40 and 80 bar. The thermal fuel power is 5 MW, which corresponds to a fuel throughput of approx. 1 t h^{-1} at a mean calorific value of 18 MJ kg^{-1} .

The Biosyncrude® produced in the fast pyrolysis is preheated to approx. 40–120 °C, pressurized, atomized by means of steam in a central multicomponent burner, and converted with oxygen into synthesis gas at temperatures above approx. 1200 °C. A backing flame fueled by natural gas ensures ignition and stability in case of inhomogeneities in the Biosyncrude®. Raw synthesis gas and slag are extracted by means of a quench system below the reactor.

In view of the high ash content of the biogenic feed materials to be used, the bioliq® pilot gasifier is equipped with a cooling screen covered with a layer of refractory material. Temperature management in the gasifier, in line with the slag fusion properties of the biomass ash, produces a firmly adhering coat of slag

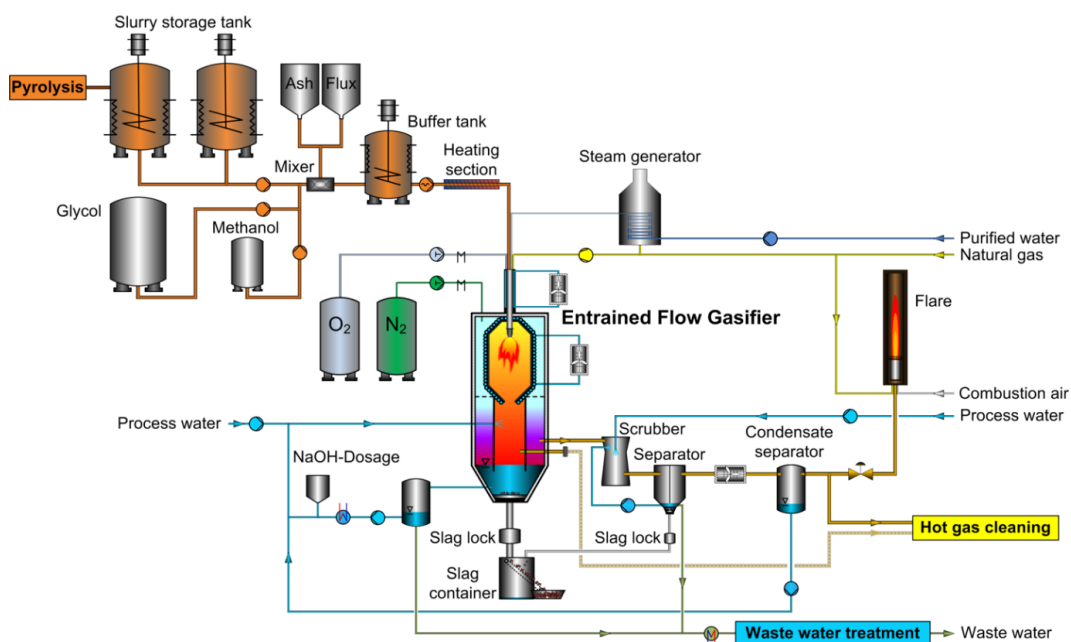


Figure 2. Process flowsheet of the high-pressure entrained-flow gasifier.

attached to the refractory lining, which protects the refractory material from abrasion and the cooling screen from corrosion. The liquid slag melt is extracted through a water quench system followed by a slag locker. In addition to the good tolerance of high-ash fuels, the cooling screen ensures a long lifetime of the reactor and the possibility of fast startup and shutdown for safe operation.

The modular design of the pilot gasifier allows the gasifier geometry to be adapted to the flow and reaction requirements of the gasification process. Consequently, two cooling screen geometries and corresponding burner dimensions are available for the two operating pressure levels of 40 and 80 bar. The cooling screen is subdivided into segments which allow local heat removal from the reaction chamber to be determined over the length of the reactor.

The gasification reactor has accesses for measurement. The flow and reaction processes in the reaction chamber can thus be described on the basis of detailed measured data. The reactor can be equipped with two quench systems: (i) a dipped quench system with annular nozzles and a wetted tube, and (ii) a free quench system with several individual nozzles and a dip tube protecting the reactor wall from excess temperatures. The plant has so far been operated with the dip quench system.

The facility is operated in the 24/7 continuous mode for individual measurement campaigns: (i) to collect operating data for a broad spectrum of feed materials, and (ii) to provide synthesis gas for the downstream synthesis of gasoline. Since commissioning, roughly 920 t of slurry were successfully converted into raw synthesis gas in 1220 h of operation.

To evaluate test runs, the pilot plant was equipped with measuring equipment so that, among other things, complete mass, species, and energy balances within the limits of balancing (Fig. 3) are possible. The data collected supplied quantita-

tive information about the assessment of economic viability of the overall process.

Balancing area 1 is used to establish mass and species balances. Balancing area 2 includes balancing area 1, at the same time taking into account the heat flows removed by the individual cooling systems, thus allowing a closed energy balance to be established. The readings obtained at the individual measuring points can be traced online by the process instrumentation and control system. An internal web portal allows access to a database containing all test runs. Tab. 1 contains the flows of materials supplied to and removed from the facility as well as the chemical components analyzed for the test runs.

The flows of Biosyncrude[®] (slurry), oxygen, nitrogen, natural gas, and synthesis gas are measured redundantly by Coriolis measuring gear (Promass83, Endress+Hauser). The individual steam flows are measured by orifice meters (Deltatop DO62C, Endress+Hauser). Industrial water used as a quenching medium and for particle separation in the Venturi scrubber and the cooling water flows are measured by a rotameter (H250, Krohne). Ultrasonic measuring gear (Proline Personi Flow 93P, Endress+Hauser) measures the waste water flows discharged discontinuously. A balance determines the slag volume discharged through the locks into a container. The process water volumes arising are examined for solids content and for organic and inorganic elements and compounds. Together with the analyses of ash and slag, this provides a complete picture of the origins and whereabouts of individual trace elements.

In addition to the described instrumentation, a camera system was developed aiming at online monitoring of the multi-component burner tip and the initial part of the flame. The camera system consists of a water-cooled probe installed at an angle of 25° to the burner axis at the reactor head (Fig. 4). A pressure- and heat-resistant nitrogen-purged protection lens installed at the tip of the camera probe enables the operation of

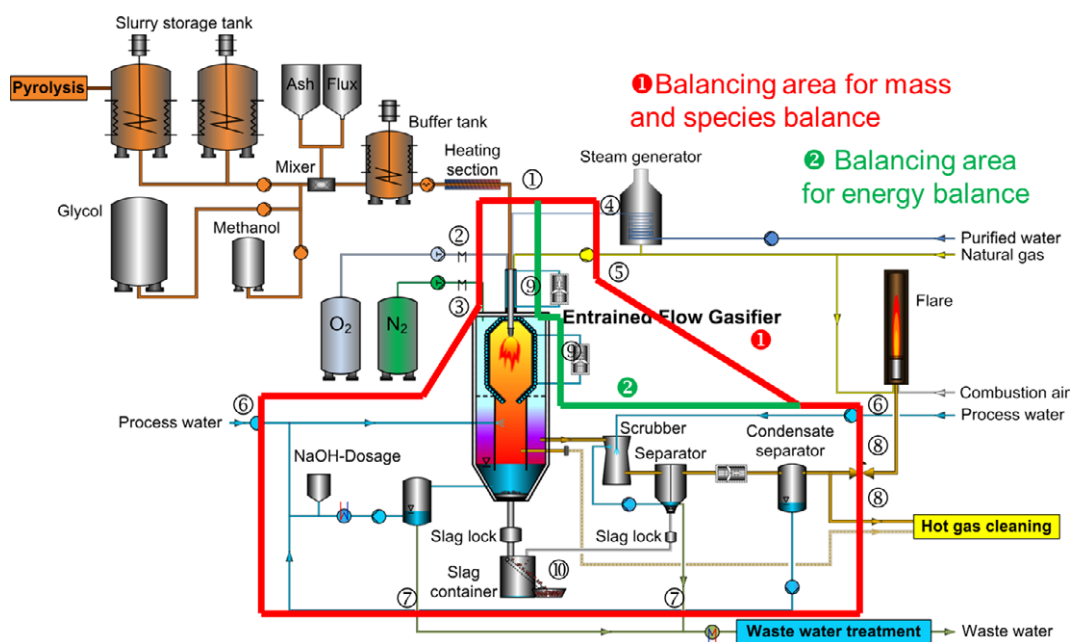


Figure 3. Balancing areas, high-pressure entrained-flow gasifier.

Table 1. Input and output flows for balancing the high-pressure entrained-flow gasifier.

Input Flows	Output Flows
1 Slurry: C, H, N, O, Cl, S Analysis: (C, H, O, N, Cl, S, H ₂ O, ash)	7 Waste water: O, H, dissolved elements Analysis: (bulk: CH ₂ O ₂ , CH ₃ COO ⁻ , Cl ⁻ , PO ₄ ³⁻ , SO ₄ ²⁻ , CN ⁻ , B, Ca, K, Mg, Na, P, S, Si, NH ₄ -N)
2 Oxygen: O, N	8 Synthesis gas: C, H, N, O, S Analysis: (H ₂ , CO, CO ₂ , CH ₄ , H ₂ S, N ₂)
3 Nitrogen: N, O	10 Slag O, Si, K, Mg, P, Na, etc. Analysis (bulk): SiO ₂ , K ₂ O, CaO, MgO, P ₂ O ₅ , NaO, traces (C et al.)
4 Steam: O, H	11 Waste heat: Synthesis gas cooler
5 Natural gas: C, H, N, O	12 Waste heat: Quench water cooler
6 Industrial water: O, H	
9 Cooling water	9 Cooling water

the camera and optics within the probe under atmospheric pressure conditions. In emergency situations when the protection lens breaks, the pressure-resistant camera probe is automatically flushed with high-pressure nitrogen, preventing hot synthesis gases from escaping the reactor.

The interior of the camera system consists of an endoscope with a remote-controlled motor focus. A view angle of 45° and an angular aperture of 60° allows a direct view of the burner tip and the initial part of the flame. Different camera systems in the visual spectral range (VIS), e.g., a high-speed camera or a high-dynamic-range camera can be mounted on the endoscope. The live camera images are transferred to the control room display and can be recorded for scientific analysis.

5 Evaluation of Operating Runs

Accompanying research into the bioliq[®] entrained-flow gasifier is being carried out within the *Energy Efficiency, Materials, and Resources* (EMR) energy research program of the HGF and the *Helmholtz Virtual Institute Gasification Technology* (HVIGas-Tech) joint research cooperation [9]. This is where the following subprocesses are being studied: (i) atomization of high-viscosity suspensions under pressure [10], (ii) heterogeneous reaction kinetics of coke particles [11], (iii) heat transport of particles and gas at high pressure [12], and (iv) slag production and factors influencing slag flow [13]. Moreover, measuring techniques are being developed for application in high-pressure

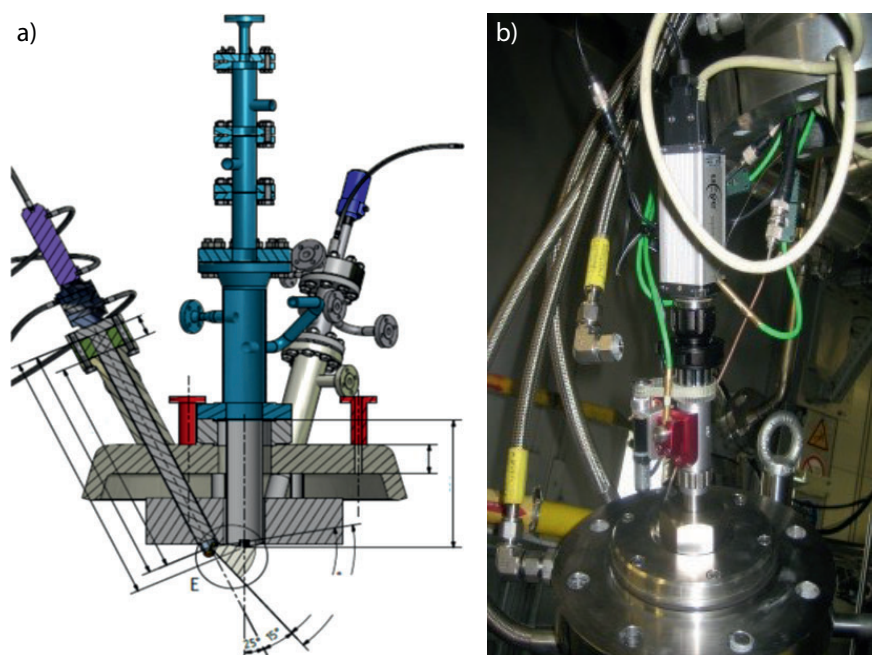


Figure 4. (a) Camera probe and the multicomponent burner installed at the top of the reactor; (b) Interior of the camera system showing the camera, motor focus and part of the endoscope.

entrained-flow gasification. The respective investigations are carried out in laboratories and pilot plants of KIT and partners in research. Research findings are combined in a simulation tool describing gasification of suspended fuels at high pressure in the entrained-flow gasifier, serving both to design and scale up technical-scale gasifiers and to optimize gasifier operation.

Operation of the bioliq[®] pilot-scale gasifier, on the one hand, serves to accumulate experience in plant operation with different feedstocks and to optimize the operating process and plant technology and, on the other, to supply process data both for modeling the subprocesses in the gasifier and for validating the simulation tool. For these purposes, the plausibility of the process data generated in the pilot gasifier under technically relevant process conditions must be ensured, which is why the gasifier, as described above, was equipped with extensive measuring systems allowing the individual operating runs to be evaluated in terms of mass, species and energy balances. Evaluation of the operating experiments is given below, and some specific results are described.

5.1 Fuel Analyses

Fuel analysis is one of the most sensitive parameters in balancing an operating point. Each batch of fuel used is analyzed for its elemental composition, calorific value, water and ash fractions, ash composition, ash fusion temperatures, temperature-dependent viscosity and particle size distribution. Since the system was commissioned, a variety of fuel mixes have been used in the entrained-flow gasifier. For good reproducibility of operating experiments, monoethylene glycol was chosen as the liquid component of a model fuel. Moreover, commercial-

grade pyrolysis oils based on the wood- and straw-based pyrolysis oils generated in bioliq[®] fast pyrolysis were used. Depending on the objectives of the study, coke from wood, coke from straw, straw ashes or glass beads were used as solid components of the suspension fuel. Coke derived from wood is a commercially produced type of charcoal, ground under defined conditions for the experiments. Coke derived from straw is the solids fraction of fast pyrolysis in the bioliq[®] process. This straw-based coke contains the bulk of inorganic substances contained in the slurry. Straw-based ashes are oxide ashes from the cleaning of flue gas from straw combustion. Glass beads, like glycol, serve for the production of model fuels which, unlike biomass-based feedstocks, are not subject to natural variation and consequently allow more precise evaluation.

The calorific values of fuels in these experiments varied between 14.5 and 22.7 MJ kg⁻¹. The main causes of the large bandwidth of calorific values are

the contents of water and ashes varying as a function of biomass feedstock and pretreatment. Tab. 2 shows the compositions of four fuels by way of example.

Table 2. Model fuel analysis.

	Slurry 34	Slurry 52	Slurry 53	Slurry 95
C [wt %]	45.7	55	51.2	39.94
H [wt %]	7.45	6.21	5.8	4.42
N [wt %]	0.5	0.13	0.77	0.1
O [wt %]	46.4	31.2	23.5	26.16
S [wt %]	0.09	0.12	0.13	0.04
Cl [mg kg ⁻¹]	0.2	0.113	0.09	0.03
Water [wt %]	1.8	4.5	13.71	25.25
Ash (550 °C) [wt %]	3.5	4.7	3.6	4.1
Calorific value [MJ kg ⁻¹]	18 779	22 140	20 740	15 389

In slurry 34, the model fuel was glycol mixed with 25 % coke derived from wood and 5 % of ashes derived from straw. As a result of the mix with high-calorific coke, the calorific value of 18.8 MJ kg⁻¹ is slightly higher than that of glycol, which is 17 MJ kg⁻¹. High-calorific wood pyrolysis oil 1 was mixed with 5 % ashes derived from straw in slurry 52. Slurry 53 represents a typical composition of the pyrolysis condensate produced in

bioliq[®] fast pyrolysis, to which again 5 % of straw-derived ashes was added. The lower range of calorific values is represented by slurry 95. In this fuel, wood pyrolysis oil 2 was mixed with a higher water content and 5 % glass beads.

5.2 Analysis of Synthesis Gas

The composition of synthesis gas is determined by two independent measuring systems. For this purpose, the gas is expanded to 1.5 bar in a small heated expansion station before being introduced into the flare and fed to a gas chromatograph to assay the main components, H₂, CO, CO₂, N₂ and CH₄. Another measuring point is located just downstream of the reactor. This is where the gas is also expanded, then cooled and analyzed in a mass spectrometer.

Depending on process conditions and feedstock, the composition of the dry synthesis gas was in these ranges: hydrogen 26–35 vol %, carbon monoxide 27–39 vol %, carbon dioxide 14–28 vol %. Methane concentration, as a rule, was below 0.1 vol %. The difference from 100 % is constituted by nitrogen used for flushing. The H₂/CO ratio, which is important in synthesis processes, was between 0.75:1 and 1:1.

5.3 Analysis of Ashes and Slags

In biogenic fuels, the quantity and composition of inorganic elements varies considerably as a function of the region of cultivation and type of plant. Tab. 3 shows the model composition of ash and the associated slag for a fuel (slurry 52) used in the bioliq[®] gasifier. For ash analysis, the fuel was ashed at 550 °C under oxidizing conditions according to DIN 5179, and subsequently the ash constituents were determined by borate extraction according to DIN 51729-1 and X-ray fluorescence analysis (RFA). The slag was washed and also analyzed by RFA.

Table 3. Ash and slag compositions from slurry 52.

	Ash	Slag
CaO [wt %]	8.24	8.01
K ₂ O [wt %]	26.84	20.89
MgO [wt %]	1.47	2.41
Al ₂ O ₃ [wt %]	1.2	1.2
SiO ₂ [wt %]	56.32	63.72
P ₂ O ₅ [wt %]	2.30	2.16

The main components of biogenic ashes are silicon, potassium, and calcium. Moreover, there are low concentrations of magnesium, aluminum, and phosphorus. Comparison of the compositions of ashes and slags reveals a shift in component fractions as a result of gasification. The species balances in Sect. 6.2 are meant to elucidate these effects as a function of ash composition and process data.

To ensure stable operation of entrained-flow gasification, the temperature in the reaction space must be selected so that, on the one hand, the slag flows reliably out of the system and, on the other hand, a stable coat of slag is built up on the membrane wall. So, besides the compositions of ashes and slags, the fusion characteristics of the slag must also be determined. For this purpose, four characteristic temperatures are determined according to DIN 51730 (1998–4) (i) in advance of an experiment in the ashes of the fuel and (ii) after the experiment in the resultant slag. Tab. 4, for example, shows three different slags with the characteristic temperatures describing fusion behavior.

Table 4. Fusion behavior of various slags.

	Slag V42	Slag V46	Slag V59
Softening point temperature [°C]	825	870	770
Spherical temperature [°C]	909	962	824
Hemispherical temperature [°C]	1108	1186	1041
Flow temperature [°C]	1299	1319	1157

In V42, the slag was produced from a mix of wood pyrolysis oil 1 and straw-derived ash (slurry 52). V46 is a type of slag derived from an experiment with glycol and straw-derived coke. The respective temperatures are slightly higher in this case than that of the slag in V42. A slag derived from wood pyrolysis oil 2 and glass beads is shown in V59. The flow temperature of this slag is about 150 K lower. As a consequence of the almost identical onset of sintering, the temperature range up to the yield point in this glass bead-based slag thus is also nearly 150 K lower, i.e., the transition from first softening to yielding occurs in a narrower range of temperatures. This property has clear impacts on the mode of operation of the reactor.

Other physical properties of bioliq[®] slags, such as viscosity, heat capacity, density, and surface tension, are shown in [14]. A study of particle size distribution of slag as discharged from the system is covered in [15].

6 Results

6.1 Mass, Species, and Energy Balances

Fig. 5 shows the development over time (PLS plot) of a number of selected plant data in test run V42 with slurry 52. The minor fluctuations in measured data caused by the mode of operation are averaged over the balancing period. The PLS record clearly shows the steady-state character of the plant during the experiment. The mass, species, and energy balances of this test run are shown in Fig. 6.

Definition of the balancing areas and logging of the process data is described in detail in Sect. 4. The mass flow at the reactor inlet (“input”) of 1970 kg h⁻¹ is composed of the individual flows of slurry, natural gas, oxygen, water vapor, and nitrogen. The other mass flows are clearly attributed in Tab. 1. The mass flow balance indicates a balancing error of 2.6 %.

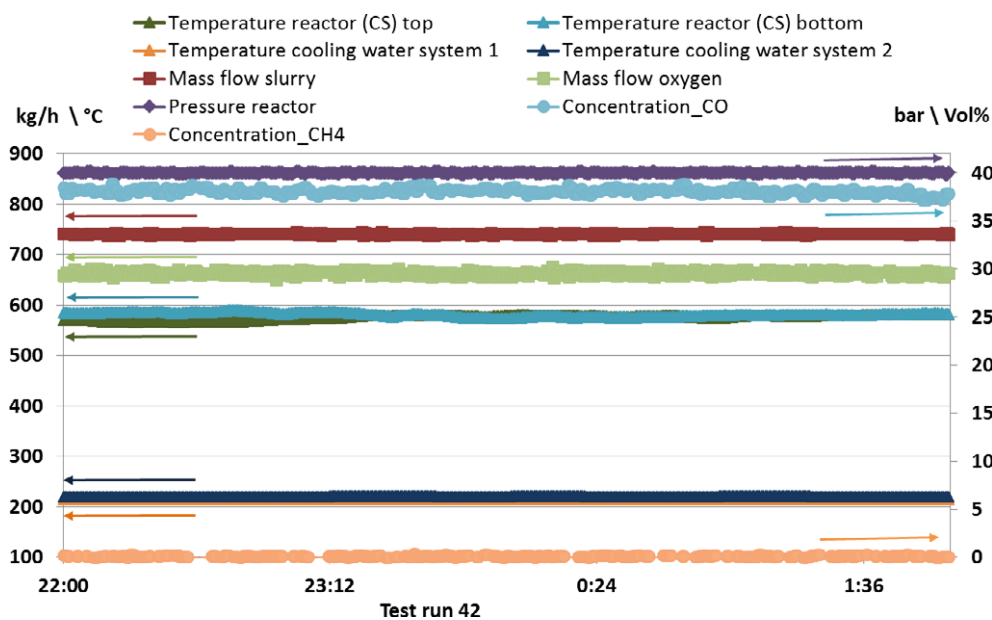


Figure 5. Time lines of characteristic operational data.

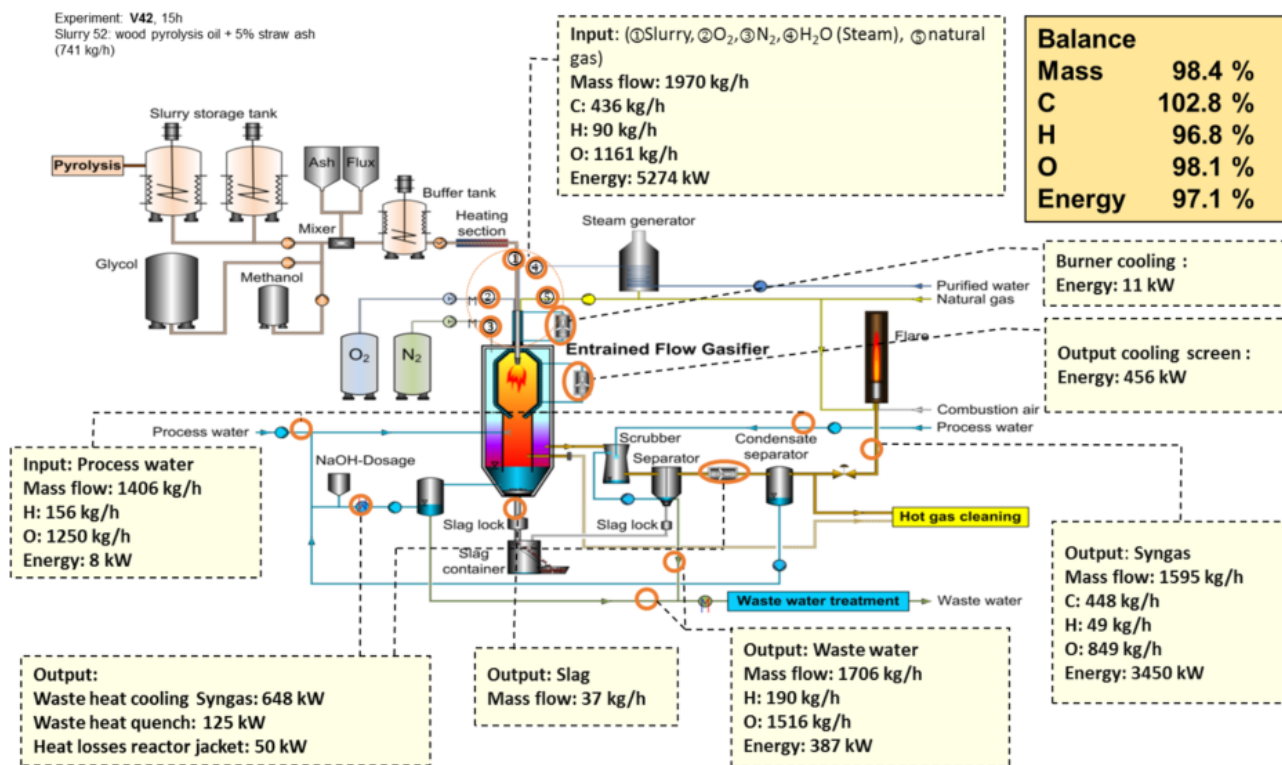


Figure 6. Mass, species, and energy balances.

The input energy flow of 5274 kW includes 5 MW of chemical energy as slurry and natural gas, plus 274 kW thermal energy via the flows of slurry, steam, and oxygen. In the output flows ("output"), the synthesis gas with a chemical energy of 3370 kW and a thermal energy content of 80 kW makes up the biggest share. The highest thermal energy flows are dissipated

by way of the quenching water (648 kW) and cooling screen (456 kW) coolers. On the other hand, water condensation in the synthesis gas upstream of transfer to the gas cleaning stage (synthesis gas cooler, 125 kW) and the loss due to heat dissipation to the environment from the outer shell (50 kW) are small. The error in the energy balance is around 2.9%. The

C/H/O species balances also show balancing errors on the order of 2–3 %.

The bioliq[®] gasifier is the only entrained-flow pilot gasifier in the world that can be balanced completely. The balancing errors shown in the example, in the order of a few percent (approx. $\pm 3\%$), must be considered very small for a technical system. The typical balancing errors in bioliq[®] operating runs are in the order of approx. 5 %. Experiments with balancing errors in excess of 10 % were not considered in the evaluation.

6.2 Balance of Inorganic Components

Slag analyses together with analyses of the industrial water input and the liquid effluent output are parts of the balance of key inorganic elements. Tab. 5 shows two examples of a balance of this type.

Test point V34, with 5 % of straw-derived ash in wood pyrolysis oil 1, shows approx. 56 % of the mass of ash of the fuel to be present in the mass of slag. Elements such as chlorine and, in part, potassium, are not present in the slag at all, or only in part, but are discharged from the system together with the liquid effluent. Because of the low concentrations and high mass flows, these balances are extremely sensitive to errors in the analyses. Further elements discharged from the system together with the synthesis gas are not taken into account.

To check the accuracy of the data obtained with this system, a feedstock made up of wood pyrolysis oil 1 and glass beads was produced for V62. To minimize influences of fresh water, fully demineralized water rather than tap water was used for this experiment. Obviously, elements from the silicate matrix of the glass are dissolved significantly less and, therefore, are integrated almost completely in the slag. The retrieval rate is nearly

100 %. Deviations in the potassium balance are due to the relatively high inaccuracies of analysis at very low concentrations.

6.3 Heat Removal through the Membrane Wall

Next to recooling of the quenching water, it is through the cooling screen that the highest energy flows are extracted from the process as lost heat. The measuring equipment not only allows overall heat removal from the cooling screen to be determined, but also makes it possible to establish a heat balance over individual segments of the cooling screen. Fig. 7 shows the overall heat removal from the cooling screen plotted against the adiabatic reactor temperature for various plant runs.

The adiabatic reactor temperature indicated in Fig. 7 is the temperature calculated with an ASPEN[®]plus equilibrium model of the gasifier using measured mass flows, elemental composition and HHV (higher heating value) from input streams. Heat removal and dissociation is not included. The diagram shows a linear relation between heat removal through the cooled reactor wall and adiabatic reactor temperature. This is indicative of heat transfer being dominated by convection between gas flow and reactor wall. The influence of radiation seems to play a subordinate role in this case, although this information needs to be verified by detailed evaluations and model simulations. The pronounced fluctuation of measured data may be due to (i) the influence of ash or slag fusion properties on the thickness of the slag film on the membrane wall, and (ii) different temperature distributions in the reactor. Other test runs are being performed to clarify this situation, but the results of numerical simulation from the work of HVI GasTech will also contribute greatly.

Table 5. Balance of main inorganic components.

Experiment	Element	Fuel input [kg h ⁻¹]	Water input [kg h ⁻¹]	Slag output [kg h ⁻¹]	Liquid effluent output [kg h ⁻¹]	Out/In [%]
V34 slurry 43–3.6 % ash	Cl	0.791	0.068	0.002	0.816	95
	Ca	1.24	0.22	0.84	0.112	65
	K	4.41	0.007	2.107	1.69	86
	Mg	0.325	0.028	0.21	0.039	70
	Si	5.12	0.01	3.2	0.219	67
	P	0.203	0.0002	0.146	0.006	74
	Ash – Slag	20.3		11.8		56
V62 slurry 93–9.09 % glass	Ca	4.12	0	4.31	0.052	106
	K	0.335	0	0.17	0.008	53
	Mg	1.6	0	1.49	0.009	94
	Si	20.69	0	21.16	0.199	103
	Na	6.19	0	6.21	0.270	105
	Ash – Slag	65.6		64.5		98

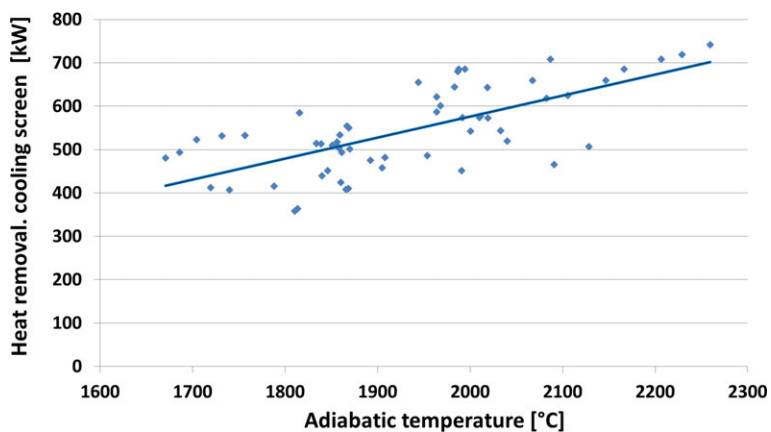


Figure 7. Heat removal from the cooling screen plotted versus adiabatic reactor temperature.

6.4 Camera-Based Flame Geometry

Image sequences recorded by the camera system described in Sect. 4 can be used for scientific analysis of the optical flame behavior. This includes the analysis of the flame geometry as well as of flame dynamics and flow properties.

As a first example, an image sequence captured with a VIS-camera at 50 fps was evaluated with respect to flame geometry (Fig. 8a). Due to the optical distortion of the endoscope a checkerboard-based camera calibration is first performed to identify a mathematical camera model that can be used to calculate undistorted images from the raw images. Second, a rectification of the undistorted images is necessary to obtain a virtual orthogonal view of the burner flame (Fig. 8b).

Based on the undistorted and rectified images, a flame detection is performed based on the mean image of the whole image sequence using a dynamic threshold method. In addition to the flame area, the opening angle of the flame is calculated by fitting a triangle flame model (Fig. 8b, green) to the flame detection (Fig. 8b, red) using a least-squares approach. In future experiments, a high-speed camera will be used. This will allow additional flicker-analyses of the flame and the investigation of the flow behavior, especially at the flame margin.

7 Summary

The bioliq[®] entrained-flow gasifier is a key technological component in the conversion of renewable resources into chemical energy carriers and base chemicals for the chemical industry with the objective of closing carbon cycles in the energy system of the future. It presents a research tool for the development of entrained-flow gasification technology up to industrial implementation.

The high-pressure entrained-flow gasifier of the bioliq[®] pilot plant is described in detail with respect to process technology and measuring systems. The tests carried out in close cooperation by KIT and Air Liquide show that the gasifier can be oper-

ated in a stable mode with a broad spectrum of fuel suspensions. Exemplary data are presented about (i) feedstocks, (ii) product specifications (synthesis gas, ash, slag), and (iii) balancing results (mass, species, and energy balances).

Acknowledgment

We are grateful to the German Federal Ministry for Food and Agriculture (BMEL) as represented by the Fachagentur für Nachwachsende Rohstoffe (FNR), the Helmholtz Association of German Research Centers (HGF), and the Baden-Württemberg State Ministry of Economic Affairs, Labour and Housing for financing the bioliq[®] pilot plant. Thanks are due to our industrial partners and plant builders, Air Liquide Engineering & Construction for financial participation, for building the plant, and for consulting within the framework of the cooperation.

The authors have declared no conflict of interest.

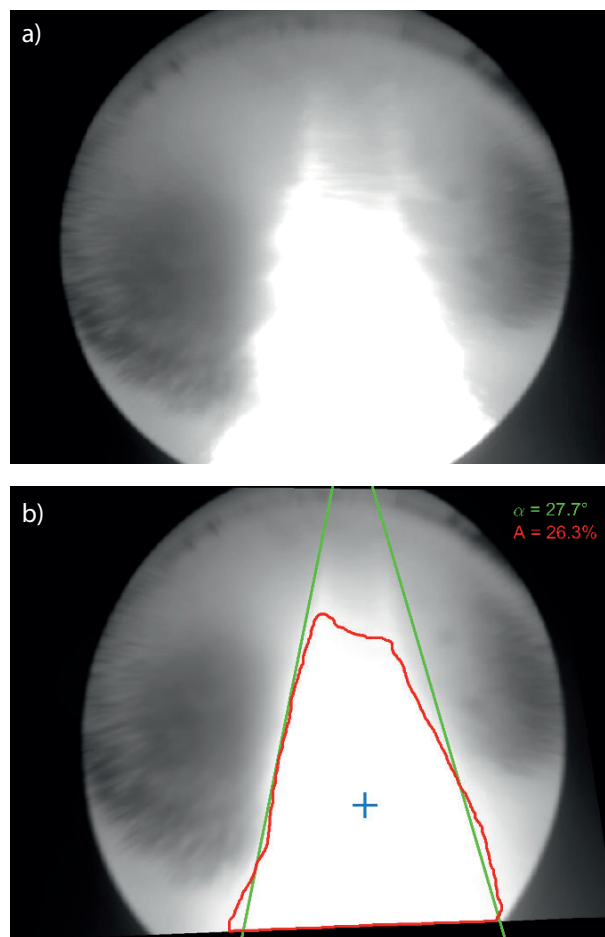


Figure 8. (a) VIS-camera raw image with bright flame; (b) probe and the multicomponent burner installed at the top of the reactor. Undistorted and rectified mean-filtered image with flame segmentation/area (red) and flame opening angle (green).



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Abbreviations

BMEL	Bundesministerium für Ernährung und Landwirtschaft (German Federal Ministry of Food and Agriculture)
BtL	biomass-to-liquid
DME	dimethyl ether
EMR	Helmholtz Program on Energy Efficiency, Materials and Resources (Energy Materials)
FNR	Fachagentur Nachhaltende Rohstoffe e.V. (Agency for Renewable Resources)
HGF	Helmholtz Gemeinschaft Deutscher Forschungszentren (Helmholtz Association of German Research Centers)
HVI	Helmholtz Virtual Institute
IGCC	integrated gasification combined cycle
MPG	multi-purpose gasification
PtX	power-to-gas/liquid (electricity produced from renewable resources for energy resources)
RFA	X-ray fluorescence analysis

Subscripts

th	thermal
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The bioliq[®] process produces synthetic fuels from dry biomass residues. The concept is to decentralize energy concentration to make the transport of biomass over longer distances economically meaningful. The process chain consists of pyrolysis, gasification, gas purification, and synthesis. First experimental results from high-pressure entrained-flow gasifiers are presented in this manuscript.

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ChemBioEng Rev. **2020**, *7* (4), XXX ··· XXX

DOI: 10.1002/cben.202000006

