

A REVIEW ON DUAL FLUIDIZED BED STEAM GASIFICATION OF PELLETIZED SOLID BIOFUEL

Van Minh Duong^{a*}, Johannes Schmid^b, Hermann Hofbauer^b

^aUniversity of Chemistry and Technology Prague, Technická 5, 166 28 Prague 6, Czech Republic

^bVienna University of Technology, Getreidemarkt 9/166, 1060 Vienna, Austria

E-mail: Duong.Van.Minh@vscht.cz

Agricultural feedstock can be a sustainable biofuel option when they perform significant calorific value and high ash deforming temperature recorded. An appropriate gasification system particularly designed for solid biofuel provides an opportunity for combined heat and power generation in gas engine or gas turbine. In further, high calorific product gas, practically free of nitrogen, can be utilized for the Fischer-Tropsch synthesis of liquid biofuels and also for production of bio synthetic natural gas or other related gaseous products. The report provides an overall review on the dual fluidized bed steam gasifier performance on feedstock pellets at temperatures between 760 °C and 810 °C. Calcite (250 - 600 μm) with mainly CaCO₃ in compositions and olivine sand (100 - 300 μm) were used as bed material for the reactor. Mass and energy balances were established on the base of stationary process simulations with IPSEpro. Physio-chemical characterization of solid biofuels were analysed and their ash fusion were evaluated. The interference on steady state operation in term of bed material agglomeration effects was discussed. Various tests on solid biofuels and further investigation on co-gasification of biomass are recommended before further scale-up.

Keywords: bioenergy, biomass, solid biofuel, steam gasification

Received 09. 09. 2018, accepted 15. 11. 2018

1. Introduction

In the world today, there is a constant growing demand for energy connected directly to economy development [1]. The greater part of this growth and receives lot of interest is biofuel diversification targeted to bio-energy production, gradually replacing conventional energy sources covered by coal, oil and gas. Besides that, carbon emissions from biomass are perceived as being natural [2], implemented the objective of the Kyoto protocol.

Beside the forest residues and waste wood, agricultural wastes, mainly straw, wheat, husks, sugarcane bagasse, coconut shells, are highlighted as a potential non-woody biomass resource for heat and electricity generation due to their commodity vary widely [3, 4]. However, the availability of these residues supply depends on crops, harvesting episodes, proportion in a paddy and bio-energy use schedule [5].

Finding new, more effective and wide-ranging thermochemical conversion applications for feedstock is essential. In recent years, gasification of solid biofuel enlarges the range of its conventional technology and has been studied in details. In many conventional gasification of solid feedstock, air is required as an oxidizing agent as it is economical and drives the process autothermally. As a result, there is always significant nitrogen diluted in the syngas, and lowers heating value of product gas down to about 3-6 MJ/Nm³ (dry basis) [6]. Especially for further synthesis processes (Fischer-Tropsch synthesis of liquid biofuel, bio synthetic natural gas or other related gaseous products) this dilution is a considerable drawback. Dual fluidized bed gasification solves this problem as the gasification zone and combustion zone, which provide the en-

ergy for gasification, are separated and pure steam is used as a gasification agent.

When steam or CO₂ is used as a gasification agent, the product gas is also free of nitrogen and the calorific value of gas is higher: for steam, gasification values between 10 and 18 MJ/Nm³ (dry basis) can be reached [7, 8]. The advantage using steam instead of CO₂ is that the reactivity of steam is on average about four times higher than that of CO₂ [9], so residence times of the char in the gasification section would have to be longer and the gasification efficiency would suffer. With H₂O or CO₂ as a gasification agent, the process becomes allothermal, so the heat for the endothermic gasification reactions has to be provided externally.

Dual fluidized bed gasification tackles this issue as the combustion reactor, which provides the energy for gasification, is separated from the gasification reactor and pure steam is used as gasification agent. A number of studies were conducted in an existing 100 kW pilot plant at Vienna University of Technology [10] for testing different types of biomass [11,12], coal [13,14], sewage sludge [15], or plastics [16] as well as investigations regarding operating parameters [17] and bed materials [18].

2. Experimental design

2.1. General principle

The basic principle of the novel dual fluidized bed gasification process is shown in Figure 1. This type of gasifier works on the basis of separating the endothermic gasification from the exothermic combustion process. Since steam is the gasification medium used, the technology produces a nearly nitrogen free, hydrogen rich producer gas.

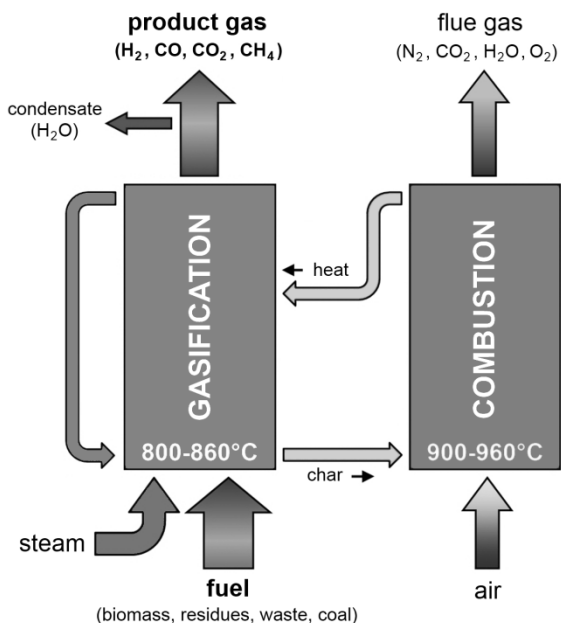


Figure 1 Schematic principle of the dual fluidized bed steam gasification process

To realize this idea two reactors are combined, with the gasification zone placed in a bubbling fluidized bed reactor and the combustion zone placed in a transporting fluidized bed reactor. Both reactors are connected via two siphons, one connecting the lower part of the gasification zone with the lower part of the combustion zone, the other connecting the lower part of the separator in the combustor with the free board of the gasifier. To guarantee nitrogen free producer gas, the two siphons are also fluidized with steam.

2.2. Novel dual reactor system

All important elements of the reactor system, as a part of the overall pilot plant equipment, are visible in the sketch of Figure 2 with top seals, process media inputs, solids separators, cyclones and the feedstock/fuel input. The system physically separates gasification and combustion, with two fluidized bed reactors connected by loop seals. Hot bed material, circulating between these two reactors, carries the required heat for gasification from the combustion reactor, where residual char together with some other fuel for combustion, if required, is burned and heats up the bed material. In a separator, the upwards-transported bed material is separated from the flue gas stream and led into the gasification zone, where the hot bed material is mixed with the fuel. The dashed line and the arrows inside the reactor system indicate the global solids circulation rate of bed material.

At the top of the gasification zone the producer gas leaves the gasifier, while at the bottom the bed material together with the residual char is transported to the combustion zone. Leakage of product gas from the gasification reactor to the combustion reactor, which would cause a loss of the valuable gas, can be effectively avoided by the loop seals. Also, any flow of air (the fluidization agent of

the combustion reactor) or flue gas through the loop seals from the combustion reactor to the gasification reactor can be eliminated as it would cause a dilution of the product gas, mainly with nitrogen.

In solid biofuel gasification, the residual char does not provide enough energy to satisfy the endothermic gasification reactions. For this reason, oil is used as additional fuel in the test facility. In industrial sized plants, a small part of the producer gas is recycled back and burned in the combustion zone. As seen in Figure 2, oil is fed into the reactor together with the primary air (5 N m³/h). The main part of the char and oil is burned in the extended part of the combustion zone where the secondary air (50 N m³/h) is introduced. Oil is also needed to control the gasification temperature, as while the circulation rate is also of course a parameter for control, regulation via the oil feed is more accurate. For that reason the fuel feed was reduced to a number where at least some oil is needed to achieve the required gasification temperature. Gasifying feedstock pellets in this reactor required the feeding system to be adjusted. The fuel input is realized via screw feeder into the lower part of the gasification reactor (on-bed feeding onto the lower bubbling fluidized bed).

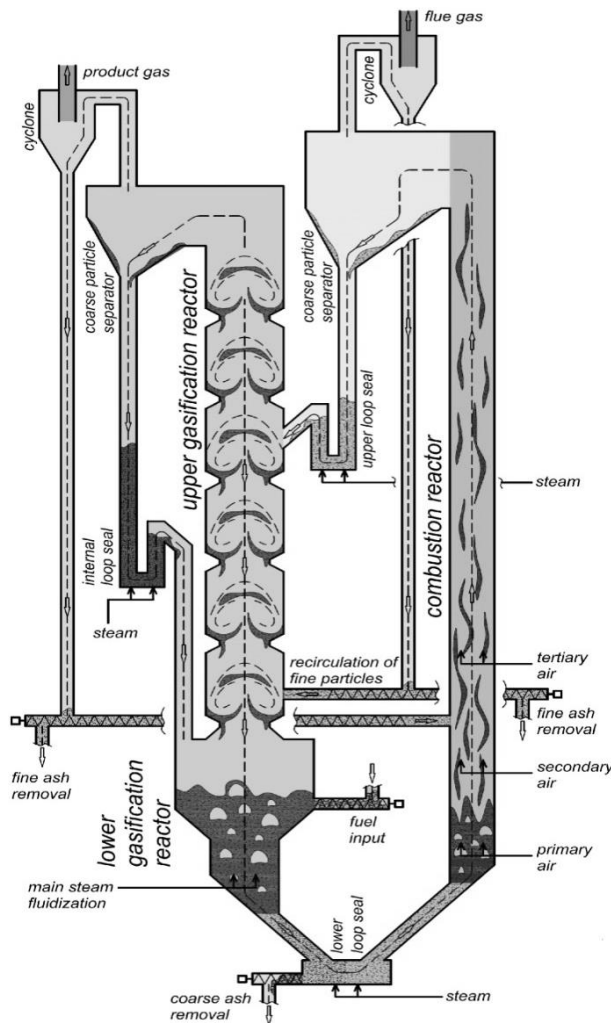


Figure 2 Schematic drawing of the dual bed reactor

There are specific requirements of the feeding system in order to ensure the transport of fuels with various calorific values and size distribution. Co-gasification with mixed fuels can be simultaneously fed from two separate hoppers and hence mixed in a chamber before being fed via a plug screw into the gasifier. Figure 3 shows the gasification reactor and the main assembled parts with insulation.

For a good reaction and mixture to occur, the fuels are fed directly into the bubbling fluidized bed. In the other option the fuel can be fed from the top onto the bubbling bed. In the test facility the gas streams from both zones are measured separately and burned together in a combustion chamber.

A producer gas cooler is essential to cool the gas while stopping all gasification reactions within the gas stream. After travelling through the gas cooler, samples are taken at two points from the producer gas stream for online producer gas measurement as well as for sampling of impurities (tars, ammonia, hydrogen sulfide, etc.). An electric steam generator provides the steam needed for fluidization of the gasification zone and the two siphons. The provided (saturated) steam has a temperature of 115 °C as it leaves the steam generator. Before the steam enters the gasifier, it is superheated to 300 °C with an electrical trace heating system.

2.3. Operation control

The range of several operating parameters for the experimental test runs, including characteristic values of the fluid dynamics, are listed in Table 1. A typical overview of a gasification test run, partially including the heat-up and shut down procedures, is displayed in Figure 4.

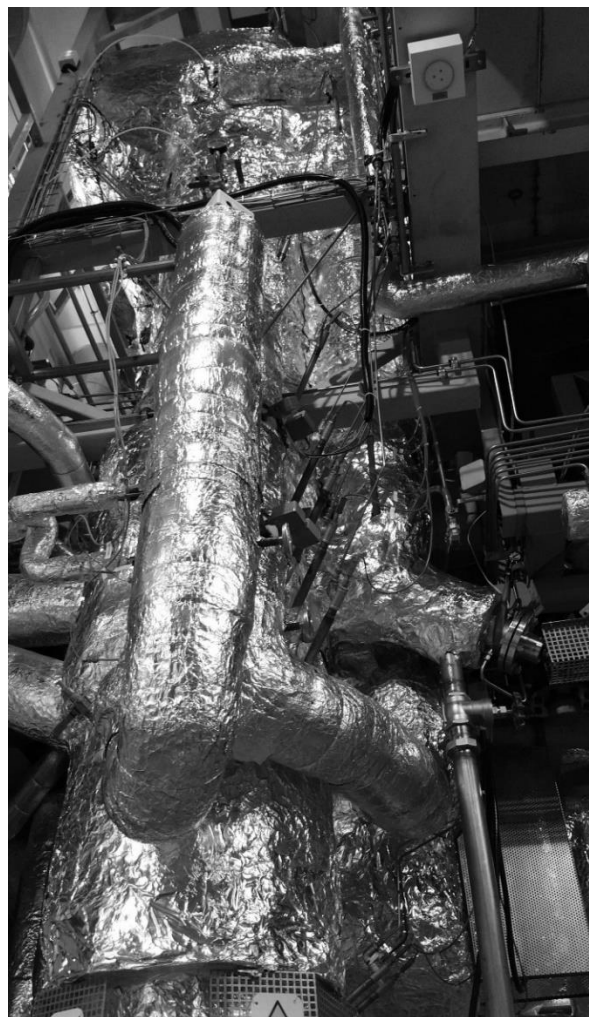


Figure 3 Dual bed reactor with insulation assembled parts

Table 1. Operational designed parameter of novel dual fluidized bed steam gasifier

Designed parameter	Unit	Lower gasification reactor	Upper gasification reactor	Combustion reactor
Temperature range	°C	700 – 850	800 – 950	830 – 980
Fluidization regime	-	bubbling bed	turbulent zones	fast bed
Input for fluidization, gasification	-	steam	steam	air
Inner diameter/dimension of reactors	mm	560 x 490; 68 x 490	128x128	ø125
Inner height of the reactors	m	1.03	3.33	4.73
Mean diameter of bed material	µm	250	250	250
Fluidization media	-	product gas	product gas	flue gas
Cross section for calculation	mm	68 x 490	128 x 128	ø125
Superficial gas velocity, U	m/s	0.47 – 0.93	1.7 – 2.1	6.3 – 7.6
Minimum fluidization velocity, U _{mf}	m/s	0.037	0.037	0.028
Fluidization ratio, U/U _{mf}	-	13 – 25	40 – 55	220 – 270
Terminal velocity, U _t	m/s	2.06	2.06	1.61
Fluidization ratio, U/U _t	-	0.23 – 0.45	0.8 – 1.1	3.8 – 4.8
Included separator system	-	freeboard zone above bubbling bed	gravity separator followed by a cyclone	gravity separator followed by a cyclone

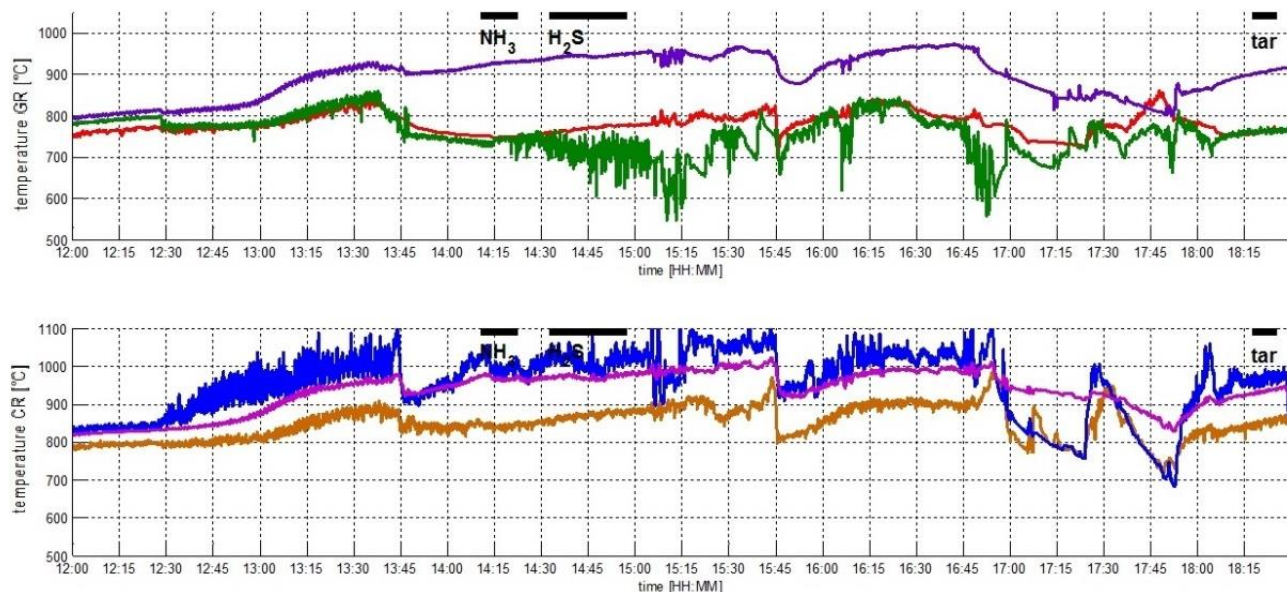


Figure 4 Temperature overview of the gasification (top) and combustion (bottom) reactors

Electrical heating started at 6:00 and at around 10:00 auxiliary fuel was introduced into the combustion reactor to increase the temperature. Fuel was introduced at around 12:45 as auxiliary fuel into the gasification reactor to reach desired gasification temperatures (heat up - combustion modus). Steam was partially supplied to the gasification reactor at 13:30 and fluidization with pure steam started at around 13:45. At 15:45 a fresh charge of calcite (10 kg) was added to the initial bed material inventory and at 20:00 again 5 kg fresh calcite were added. Operational gasification conditions for gasification test run were reached at 14:00. The steady-state operation for the test run with over 100 kW fuel power was reached and NH_3 in the product gas was measured. Directly next operation following by similar adjustments was reached and H_2S content in the product gas was measured.

During this part of operation the temperature in the lower gasification reactor began to drift and fluctuate. The fuel input was therefore stopped at 15:15 because a stationary state was not reached due to ash formation issues. After 15 minutes there were no more bed fluidization and so fuel input had to be stopped. The tackle of problems took a time, last stationary state was reached at 18:10. Tar, dust, char and water content were measured. Then the operation was changed to lower gasification temperatures to avoid the ash melting related issues.

Table 2 Typical value of solid biofuel test runs

Parameter/name	unit	value
Gasification reactor	kW	40 – 110
Feedstock properties	-	pellets
Heat losses of the reactor	kW	25 – 30
Additional fuel input for temperature regulation & compensation heat losses	kW	30 – 57
Pressure	bar	ambient
Amount of bed material	kg	75 – 100

2.4. Bed material

In the dual fluidized bed concept, the circulating bed material serves as a heat carrier to promote the endothermic gasification reactions. Calcite (250 – 600 μm) and olivine sand (100 – 300 μm) are usually used as bed material for the fluidized bed reactors during the test runs of the novel pilot plant as shown in Figure 5.



Figure 5 Mixture of calcite as bed material

Tables 3 and 4 summarize the elemental compositions of different bed material types. Previous studies indicate that olivine can be catalytically active in terms of tar degradation [19,20]. Additionally, the bed material calcite is able to act as a CO_2 carrier. The initial bed material mass typically 70kg contains mainly calcite (80 wt.%) and 20 wt.% olivine. Fresh charges of bed material mixture (5 – 10 kg) is commonly added during the runs.

Table 3 Elemental compositions of calcite

Parameter/name	unit	value
CaCO ₃	wt. %	95 – 97
MgCO ₃	wt. %	1.5 – 4.0
SiO ₂	wt. %	0.4 – 0.6
Al ₂ O ₃	wt. %	0.2 – 0.4
Fe ₂ O ₃	wt. %	0.1 – 0.3
hardness	Mohs	3
particles density	kg/m ³	≈ 2650
particles density (after full calcination)	kg/m ³	≈ 1500

Table 4 Elemental compositions of olivine

Parameter/name	unit	value
MgO	wt. %	48 – 50
SiO ₂	wt. %	39 – 42
Fe ₂ O ₃	wt. %	8.0 – 10.5
Al ₂ O ₃ +Cr ₂ O ₃ +Mg ₃ O ₄	wt. %	0.7 – 0.9
CaO	wt. %	< 0.4
NiO	wt. %	< 0.1
CaCO ₃	wt. %	< 0.1
trace elements	wt. %	< 0.1
hardness	Mohs	6 – 7
particles density	kg/m ³	≈ 2850

2.5. Mass and energy

Mass and energy balances for all test runs and operation phases are established via the software IPSEpro. This common used simulation tool originating from the power plant sector, offers stationary process simulations based on flow sheet handling with errors to a minimum.

The average measurement results of a specific steady state operation are the basis of the simulation work with IPSEpro. To get data, which cannot be measured directly, a mass and energy balance is used. Thus, a verification of all measured values and a determination of directly immeasurable key data such as heat losses, overall gas efficiency, product gas yields, calorific fuel conversion and absolute/relative water conversion rates are obtained.

Table 5 shows detailed results of the simulation work of the novel 100 kW gasification plant. These validated results are highly valuable and representative for the up scaling of dual fluidized bed gasification process.

2.6. Fuel analysis

As the relevant issue for all types of thermo-chemical conversion technologies, the physio-chemical characterization of solid biofuel must be analyzed and their ash fusion must be evaluated. The obtained values define the behavior of the biofuel during the gasification and combustion stages, and thus support the proper design and operation setting.

Table 5 Typical parameters and values calculated with IPSEpro mass & energy balance

Parameter/name	unit	value
Heat losses of reactor system	kW	24.5
Water content in the gas stream	vol. %	43–46
Gasification steam to fuel ratio	kg/kg	0.87
Gasification steam to carbon ratio	kg/kg	1.69
Product gas volume flow (dry basis)	N m ³ /h	23.8
Feedstock mass flow (dry basis, ash free)	kg/h	20.1
Product gas yield (dry basis)	N m ³ /kg	1.2
Steam related H ₂ O conversion	kg/kg	0.18
Fuel related H ₂ O conversion	kg/kg	0.16
Product gas lower heating value (free of char & tar, dry basis)	MJ/m ³	12.5
Product gas power (free of char & tar)	kW	82.5
Cold gas efficiency	%	78.7
Overall cold gas efficiency, novel 100kW test plant	%	58.8
Overall cold gas efficiency, estimated for a 50 MW plant	%	70–80
Product gas, H ₂ to CO ratio	-	2.4

The selected fuel type for the gasification test is shown in Figure 6. Depending on the fuel preparation process, the particle size distribution is normally homogeneous, appropriate for small-scale fuel-feeding screws. Beside the physical parameters such as particle dimensions, bulk and energy density, gross and net calorific value indicate a potential heat release and the influence the process control. Moisture content is always the first step to reduce the volume of raw materials and increase the heat exchange efficiency.

**Figure 6** Typical feedstock pellets size 6-8mm

Main elemental compositions, volatiles, moisture and ash content, as well as the ash melting behavior of the feedstock fuels are analyzed according to international standards at the test laboratory. Carbon and hydrogen, which are the main components of solid biofuel, explain the obtained calorific value. Amount of volatile matter indicates rational part of the biofuel is vaporized before homogeneous gas phase reactions take place, strongly influences the thermal decomposition. Nitrogen, sulfur and chlorine contents are important for nitrogen oxides, HCl, Cl₂, alkali chlorides formation, gaseous compounds of SO₂, SO₃ and alkali sulfates.

Additionally, ash analysis with X-ray fluorescence spectroscopy (XRF) offers an overview of the main elemental ash components. Concentration of major cations and ash-forming elements (Fe, Mn, Ca, K, Cl, S, P, Al, Mg, Na and especially Si) should be determined [21]. The alkali content is responsible for the ash softening temperature, which in practical avoids the agglomeration of bed materials, minimize the risk of breakdown of the fluidized bed system and stop the test runs at an early stage.

The ash melting behavior is determined by optical standard lab-scale testing method. Four temperatures can be specified: The deformation temperature (A), where the first rounding of the edges of a cubic sample occurs, the spherical temperature (B), the hemi-spherical temperature (C) and the flow temperature (D), where the sample is molten to a flat disk with defined geometrical conditions (specific height). The ash deformation and softening temperatures are important and critical for fluidized bed operation. Ash sintering/melting is a very complex phenomenon, which has to be prevented inside fluidized beds, since solids agglomeration and plugging may occur.

3. Discussion

In the dual fluidized bed concept, the circulating bed material serves as a heat carrier to promote the endothermic gasification reactions as shown in Figure 7. Additionally, the bed material calcite is able to act as a CO₂ carrier. If temperatures in the gasification reactor and the combustion reactor are set adequately, CO₂ is partly removed from the product gas in the gasification reactor. At the same time hydrogen production is enhanced by reactions such as the water-gas-shift equilibrium. Thus, with the sorption enhanced reforming process a product gas with higher hydrogen contents can be produced [22].

The low steam related water conversion may be a result of the unforeseen mixing behavior of the bubbling fluidized bed for some types of solid biofuel. The ongoing agglomeration effects, or a minimized specific porosity of the calcite bed material particles has extra influence on the high temperature.

Thus, the influence of a lower gasification temperature should be investigated in this sorption enhanced reforming (SER) process operated with mainly calcite as bed material.

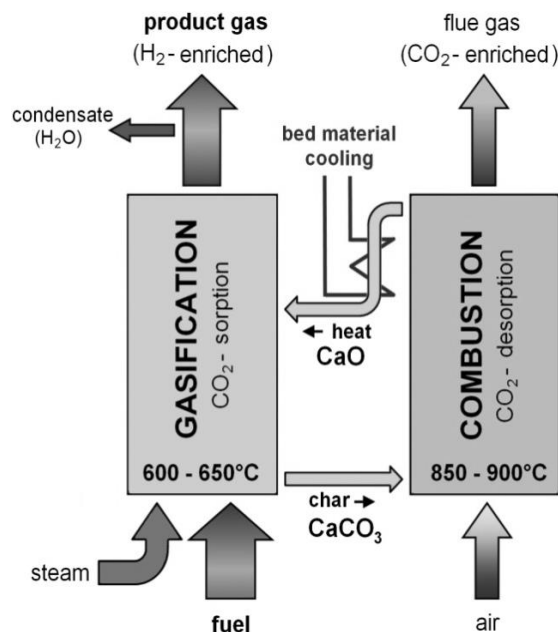


Figure 7 Sorption enhanced reforming process

Several temperature measurement points are distributed along each reactor, at different heights from the ground. Figure 8 shows the average temperature distribution in the gasification zone. The lowest temperature is at the height where the fuel is fed into the bed. The most important pressure measurement is the pressure drop in the bubbling fluidized bed of the gasifier. Since the facility works under atmospheric pressure, only pressure differences within the gasifier is needed to be measured.

Not like most of the medium and large scale systems, which are suitable to combust low-quality fuel, experimental pilot plant demands higher fuel quality concerning the homogeneity. Some types of feedstock pellets showed a potential risk of bed material agglomeration and formation of critical ash skeletons, which are going to accumulate in the reactor system. Thus, effective strategies have to be developed to avoid ash melting and ash agglomeration during the operation of the used fluidized bed before further scale-up.

Influence of the feedstock feeding position on the profiles of gas species in the gasification reactor must be investigated. In one case the fuel was fed directly into the bubbling fluidized bed, then lower tar contents and a higher H₂ content were observed. In the second case the fuel was fed from the top onto the bubbling bed, the amount of product gas generated was significantly higher.

4. Conclusions

Although a large number of studies has been conducted recent years, the report enables us to revise current progresses in allothermal gasification of feedstock. Experiments on the pilot scales operated with a dual fluidized bed steam gasification system showed the good suitability of feedstock pellets on the pilot plant.

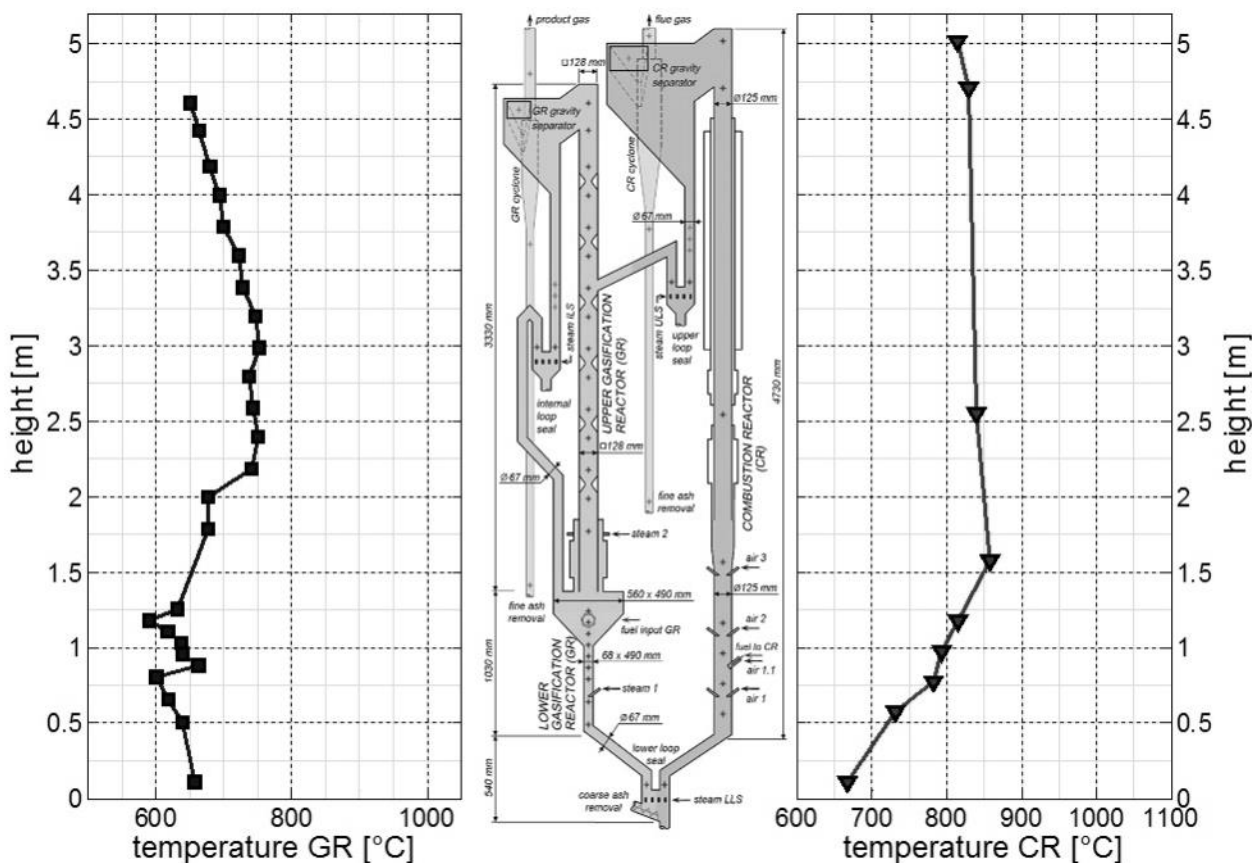


Figure 8 Vertical temperature profiles of the gasification (left) and combustion (right) reactors

In practice, the whole process of biomass utilization including material supply, fuel analysis, application design, system testing, gaseous emissions, etc., strongly depends on the physical characteristics and chemical compositions of the specific solid biofuel. Similarly like the conventional gasification, fuel flexibility is always the key feature for an economic breakthrough. While the local availability of biomass and dependence on the harvesting episodes are common issues. Therefore, various tests on other solid biofuels and research on co-gasification of biomass will need to be exercised.

The possibility of upscaling to industrial sized plant in combination with conventional fossil fuels can be considered since coal is still a significant part of future energy supplies. If so, tar content decreases with increasing biomass ratios, but is generally low if the catalytically active bed material olivine presented. Concentrations of impurities such as NH₃ and H₂S increase linearly with an increasing coal ratio due to the higher sulfur and nitrogen content of the coal. The coal ash content is also higher and so consequently the dust content of the producer gas increases with the coal ratio.

Acknowledgements

This work was carried out under the Programme Erasmus+ Key Action 1 in research exchange and staff mobility between member states. An acknowledgement

should be given the European Commission for their excellent contributions. The authors would express their appreciation to the analytical groups at University of Chemistry and Technology Prague, Vienna University of Technology and the University of Vienna for their excellent technical assistances.

References

1. International Energy Agency: World Energy Outlook; ISBN 978-92-64-28205-6, 2017, 782p.
2. Demirbas A.: Progress and recent trends in biofuels; Progress in energy and combustion science 33(1), 2007, 1-18.
3. Abe H. et al.: Potential for rural electrification based on biomass gasification in Cambodia; Biomass and Bioenergy 31(9), 2007, 656-664.
4. Chungsangunsit T. et al.: Environmental assessment of electricity production from rice husks: a case study in Thailand; International conference on electricity supply industry in transition: Issues and prospect for Asia, Thailand, 2004, Proceeding 20, 51-62.
5. Vietnam Institute of Energy.: Bagasse and other biomass-fired power plant in Ben Tre sugar company; a pre-feasibility study report; Hanoi, Vietnam, 2006.
6. Zainal Z. A. et al.: Experimental investigation of a downdraft biomass gasifier; Biomass and Bioenergy 23(4), 2002, 283-289.

7. Rapagna, S. et al.: Steam-gasification of biomass in a fluidized-bed of olivine particles; *Biomass and Bioenergy* 19 (3), 2000, 187-197.
8. Schuster, G. et al.: Biomass steam gasification - an extensive parametric modeling study; *Bioresource Technology* 77 (1), 2001, 71-79.
9. Molina, A., Mondragon, F.: Reactivity of coal gasification with steam and CO₂; *Fuel* 77(15), 1998, 1831-1839.
10. Hofbauer, H. et al.: Six years' experience with the FICFB-gasification process; *Proceedings of the 12th European Biomass Conference, ETA Florence, Italy, 2002*, 982-985.
11. Pfeifer, C. et al.: Steam gasification of various feedstocks at a dual fluidised bed gasifier: Impacts of operation conditions and bed materials; *Biomass Conversion and Biorefinery* 1(1), 2011, 39-53.
12. Kitzler, H. et al.: Gasification of reed in a 100 kW dual fluidized bed steam gasifier; *Proceedings of the 19th European biomass conference and exhibition, Berlin, Germany, 2011*, 1101-1105.
13. Kern, S. et al.: Dual fluidized-bed steam gasification of solid feedstock: Matching syngas requirements with fuel mixtures; *Proceedings of the Industrial Fluidization South Africa (IFSA 2011), Johannesburg, South Africa, 2011*, 67-78.
14. Kern, S. et al.: Synergetic utilization of renewable and fossil fuels: dual fluidized bed steam co-gasification of coal and wood; *APCBEE Procedia* 1, 2012, 136-140.
15. Schmid, J. C.: Variation of feedstock in a dual fluidized bed steam gasifier - influence on product gas, tar content and composition; *Environmental Progress & Sustainable Energy* 31(2), 2011, 205-215.
16. Wilk, V., Hofbauer H.: Co-gasification of plastics and biomass in a dual fluidized-bed steam gasifier: Possible interactions of fuels; *Energy Fuels* 27 (6), 2013, 3261-3273.
17. Kern, S. et al.: Co-gasification of wood and hard coal in a dual fluidized bed steam gasifier: process efficiency vs. gasification temperature. In: *Proceedings of the 21st International Conference on Fluidized Bed Combustion (FBC), Naples, Italy, 2012*.
18. Pfeifer, C.: Catalysts for dual fluidized bed biomass gasification - an experimental study at the pilot plant scale; *Biomass conversion. Biorefinery* 1 (2), 2011, 1-12.
19. Devi L. et al.: Olivine as tar removal catalyst for biomass gasifiers: catalyst characterization; *Apply Catalysis A: General* 294, 2005, 68-79.
20. Devi L. et al.: Pretreated olivine as tar removal catalyst for biomass gasifiers: investigation using naphthalene as model tar; *Fuel Process Technology* 86, 2004, 707-30.
21. Duong, V. M. et al.: Comprehensive evaluation of rice husks as a potential solid biofuel; *Paliva* 10 (3), 2018, 85-88.
22. Müller, S.: *Hydrogen from Biomass for Industry - Industrial Application of Hydrogen Production Based on Dual Fluid Gasification*; PhD thesis, Vienna University of Technology, ISBN: 978-3-9502754-5-2, 2013.