PHYTO2ENERGY

Phytoremediation driven energy crops
production on heavy metal degraded areas as
local energy carrier

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Report on biomass gasification and guidance on the gasification process operations improvement for utilization of HMC biomass

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VERSION RECORD

Version	Date	Author	Description of Changes
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v2	2018/01/04	C.Dima	Document supplementing
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OVERVIEW OF THE DELIVERABLE

WP:	**3**
Task :	3.3 and 3.4
Title :	T.3.3 Gasification tests of biomass (control, year 2, 3,4 yield samples) with char/ash sampling, TGA+FTIR tests T.3.4 Identification of areas for process operations improvement

Introduction

The document presents the Fixed bed gasification process results.

Fixed bed gasification - methodology

In order to implement the gasification test, as a first a test plan in a form of a technical document T.D 3.4 Gasification and TGA+FTIR tests methodology was developed. A total of four gasification tests were performed within the project. Table 1 provides a specification of the samples obtained for gasification in the experiment.

Table 1 Gasification tests

Gasification test	Year/sampling campaign	Sample origin	Sample identification	Treatment applied to the experimental plot
Test 1	2014 biomass collected after the growing season 2013	Existing old Bytom plantation	Control- old Bytom plantation	No treatment
Test 2	2015 (biomass collected after the first vegetation season)	Existing old Bytom plantation	Control- old Bytom plantation	No treatment
		Existing old Bytom plantation	Control- old Bytom plantation	EmFarma Plus application
		Bytom site (new)	Bytom new plantation	No treatment
				EmFarma Plus application
				N, P, K fertilizer application
		Leipzig site (new)	Leipzig new plantation	No treatment
				EmFarma Plus application
				N, P, K fertilizer application
Test 3	2016 (biomass collected after the second vegetation season)	Bytom site (new)	Bytom new plantation	No treatment
				EmFarma Plus application
				N, P, K fertilizer application
		Leipzig site (new)	Leipzig new plantation	No treatment
				EmFarma Plus application
				N, P, K fertilizer application
Test 4	2017 (biomass collected after the third vegetation season)	Bytom site (new)	Bytom new plantation	No treatment
				EmFarma Plus application
				N, P, K fertilizer application
		Leipzig site (new)	Leipzig new plantation	No treatment
				EmFarma Plus application
				N, P, K fertilizer application

The aim of using the biomass from the old IETU plantation (control old biomass) was two folds: to get an initial recognition on the gasification results of heavy metal contaminated biomass and to create a database of results which will serve as a baseline for comparison of results obtained from gasification of biomass collected from the newly established plots gasification in the following years of the project.

The gasification experiments are performed in a fixed bed installation provided by SUT (Figure 1 and 2).

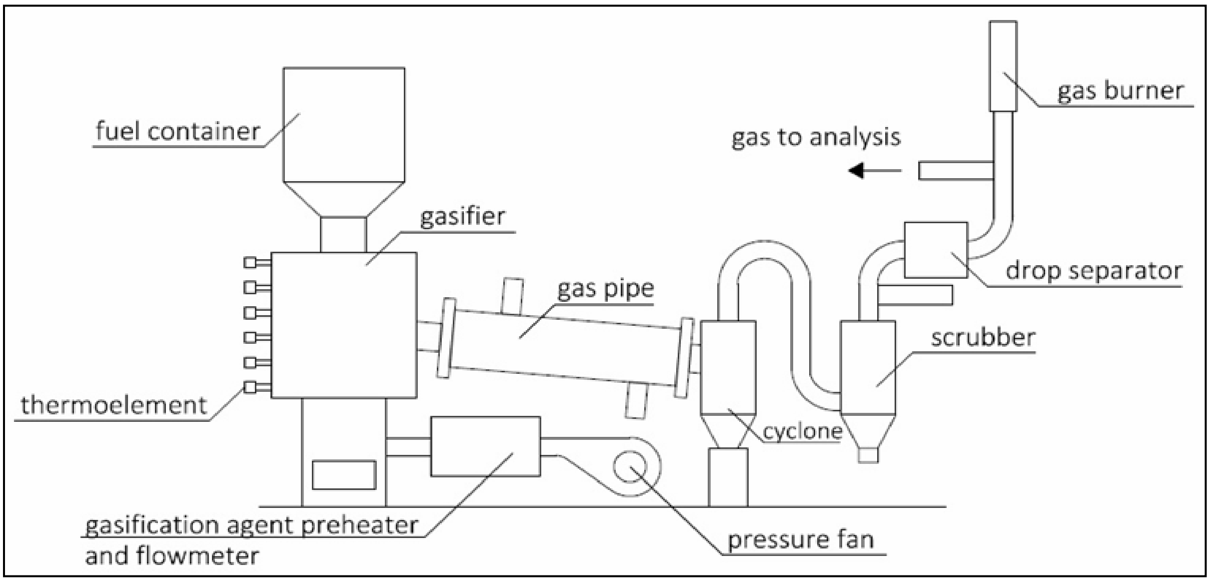


Figure 1 Fixed bed installation scheme

Figure 2 Fixed bed installation during work

For each gasification test a minimum of 5 kg of chopped biomass (each plant species) is needed.
Within project months 1-48, laboratory gasification tests of the following biomass were performed (Table 2):

Table 2 Summary of the gasification tests performed in project months 1-48

Origin of samples	Samples name used in determinations	Plant species harvested (Feedstock type)	Treatment applied	Symbols
Old Bytom plantation	Test 1 Control old biomass	*Miscanthus x giganteus* *Spartina pectinata* *Sida hermaphrodita* *Panicum virgatum*	No treatment	OB/MG/I/P OB/SP/I/P OB/SH/I/P OB/PV/I/P
			2015 - EmFarma Plus application	OB/MG/III/P OB/SP/III/P OB/SH/III/P OB/PV/I/P
Bytom site – new plantation	Test 2 Biomass after first growing season	*Miscanthus x giganteus* *Spartina pectinata* *Sida hermaphrodita*	No treatment	B/MG/I/P1st gs B/SP/I/P1st gs B/SH/I/P1st gs
			N, P, K fertilizer application	B/MG/II/P1st gs B/SP/II/P1st gs B/SH/II/P1st gs
			EmFarma Plus application	B/MG/III/P1st gs B/SP/III/P1st gs B/SH/III/P1st gs
Leipzig site – new plantation		*Sida hermaphrodita*	No treatment	L/SH/I/P1st gs
			N, P, K fertilizer application	L/SH/II/P1st gs
			EmFarma Plus application	L/SH/III/P1st gs
Bytom site – new plantation	Test 3 Biomass after second growing season	*Miscanthus x giganteus* *Spartina pectinata* *Sida hermaphrodita* *Panicum virgatum*	No treatment	B/MG/I/P2nd gs B/SP/I/P2nd gs B/SH/I/P2nd gs
			N, P, K fertilizer application	B/MG/II/P2nd gs B/SP/II/P2nd gs B/SH/II/P2nd gs B/PV/II/P2nd gs
			EmFarma Plus application	B/MG/III/P2nd gs B/SP/III/P2nd gs B/SH/III/P2nd gs B/PV/III/P2nd gs
Leipzig site – new plantation		*Miscanthus x giganteus* *Spartina pectinata* *Sida hermaphrodita* *Panicum virgatum*	No treatment	L/MG/I/P2nd gs L/SP/I/P2nd gs L/SH/I/P2nd gs L/PV/I/P2nd gs
			N, P, K fertilizer application	L/MG/II/P2nd gs L/SP/II/P2nd gs L/SH/II/P2nd gs
			EmFarma Plus application	L/MG/III/P2nd gs L/SP/III/P2nd gs L/SH/III/P2nd gs
Bytom site – new plantation	Test 4 Biomass after third growing season	*Miscanthus x giganteus* *Spartina pectinata* *Sida hermaphrodita* *Panicum virgatum*	No treatment	B/MG/I/P3rd gs B/SP/I/P3rd gs B/SH/I/P3rd gs B/PV/I/P3rd gs
			N, P, K fertilizer application	B/MG/II/P3rd gs B/SP/II/P3rd gs B/SH/II/P3rd gs B/PV/II/P3rd gs
			EmFarma Plus application	B/MG/III/P3rd gs B/SP/III/P3rd gs B/SH/III/P3rd gs B/PV/III/P3rd gs
Leipzig \`site – new plantation		*Miscanthus x giganteus* *Spartina pectinata* *Sida hermaphrodita* *Panicum virgatum*	No treatment	L/MG/I/P3rd gs L/SP/I/P3rd gs L/SH/I/P3rd gs L/PV/I/P3rd gs
			N, P, K fertilizer application	L/MG/II/P3rd gs L/SP/II/P3rd gs L/SH/II/P3rd gs L/PV/II/P3rd gs
			EmFarma Plus application	L/MG/III/P3rd gs L/SP/III/P3rd gs L/SH/III/P3rd gs L/PV/III/P3rd gs

Fixed bed gasification - results

The gasification tests for each biomass type were performed at six air ratios: 0.12, 0.14, 0.16, 0.18, 0.23 and 0.27. The gasification agent was atmospheric air with a temperature of 25°C (298K).

Molar fractions of combustible species were measured on-line. Additionally, based on the results lower heating value (LHV) in MJ/m^3N of the syngas was calculated using following formula:

$LHV=0.126 \bullet CO+0.108 \bullet H2+0.358 \bullet CH4$

Figure 3 presents the results obtained for the biomass harvested from Bytom and Leipzig new plantations for the lower heating values of resulted gas calculated at different excess air ratios.

As it can be observed that the majority of highest values for the LHV (Lower Heating Value) were obtained for an excess air ratio of 0.18. The best result is obtained from the gasification of *Sida hermaphrodita* collected from Leipzig site after 3rd growing season with NPK fertilizers (L/SH/II/P3rd gs), 4.423 MJ/m^3 (Figure 4). More than, L/SH/II/P3rd gs showed the highest values for the LHV at other excess air ratios the other biomass types, including the optimal 0.18 value (Figure 5). The results for *Sida hermaphrodita* can be partially explained by the higher values of temperature, compared to the other three types of biomass, inside the gasifier during the test. This is especially visible in the zone for the fourth and fifth temperature probes (Figure 6).

Spartina pectinata collected from new Bytom site after 1st growing season with NPK fertilizers (B/SP/II/P1st gs) showed the lowest variation of LHV between the different values of λ, 1.815 MJ/m^3 corresponding to an excess air ratio of 0.18 (Figure 7).

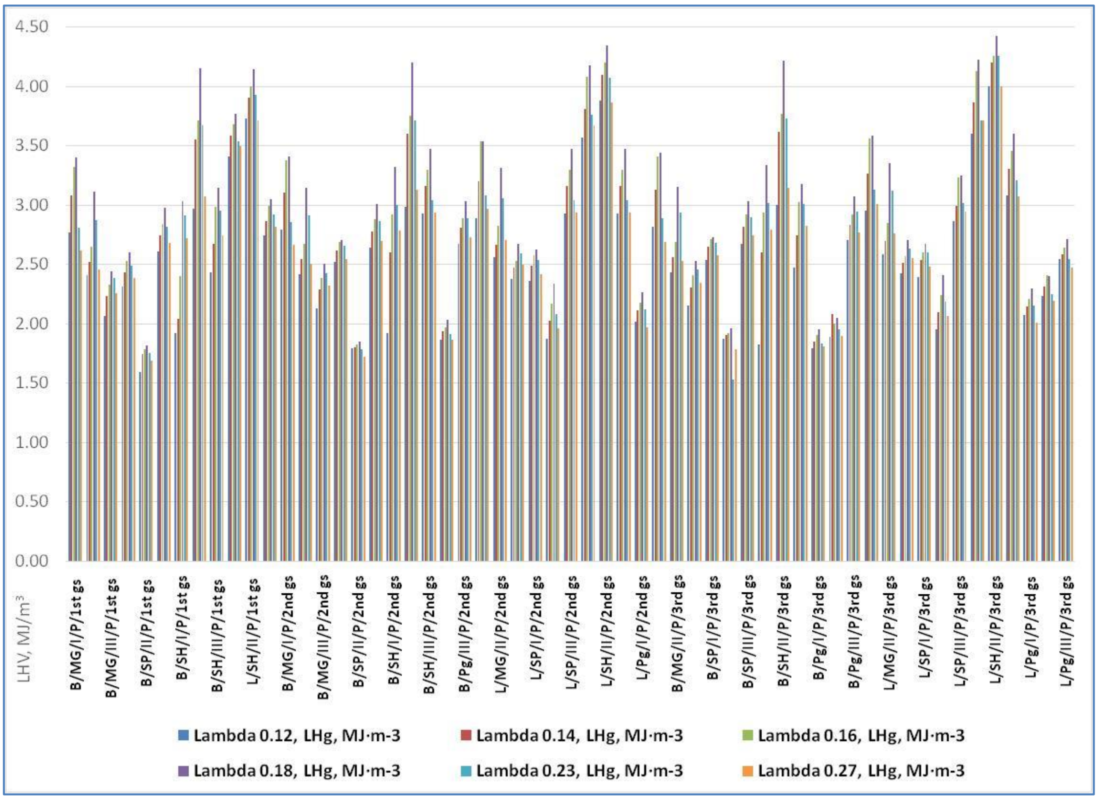


Figure 3 The lower heating value (LHV) all feedstock collected from Bytom and Leipzig new plantations after all three growing seasons

Figure 4 The lower heating value (LHV) all plants treated with NPK fertilizer collected from Bytom and Leipzig new plantations after all three growing seasons

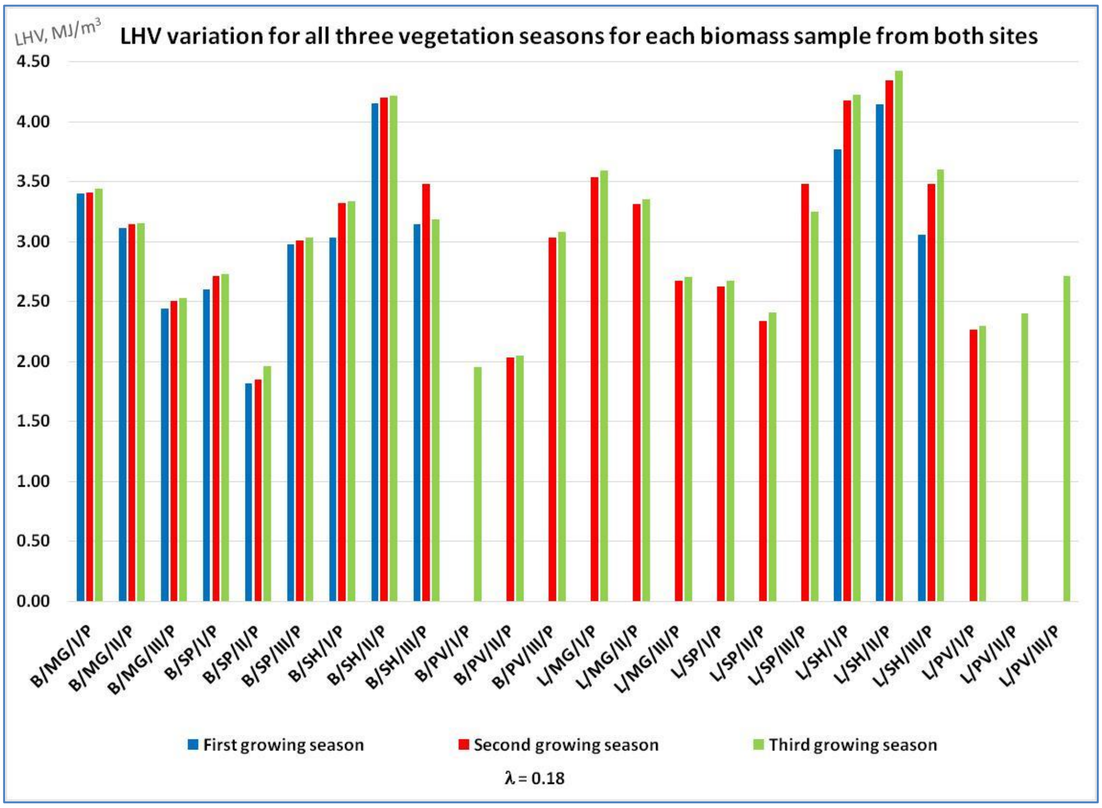


Figure 5 The lower heating value (LHV) all feedstock collected from Bytom and Leipzig new plantations after all three growing seasons corresponding to λ=0.18

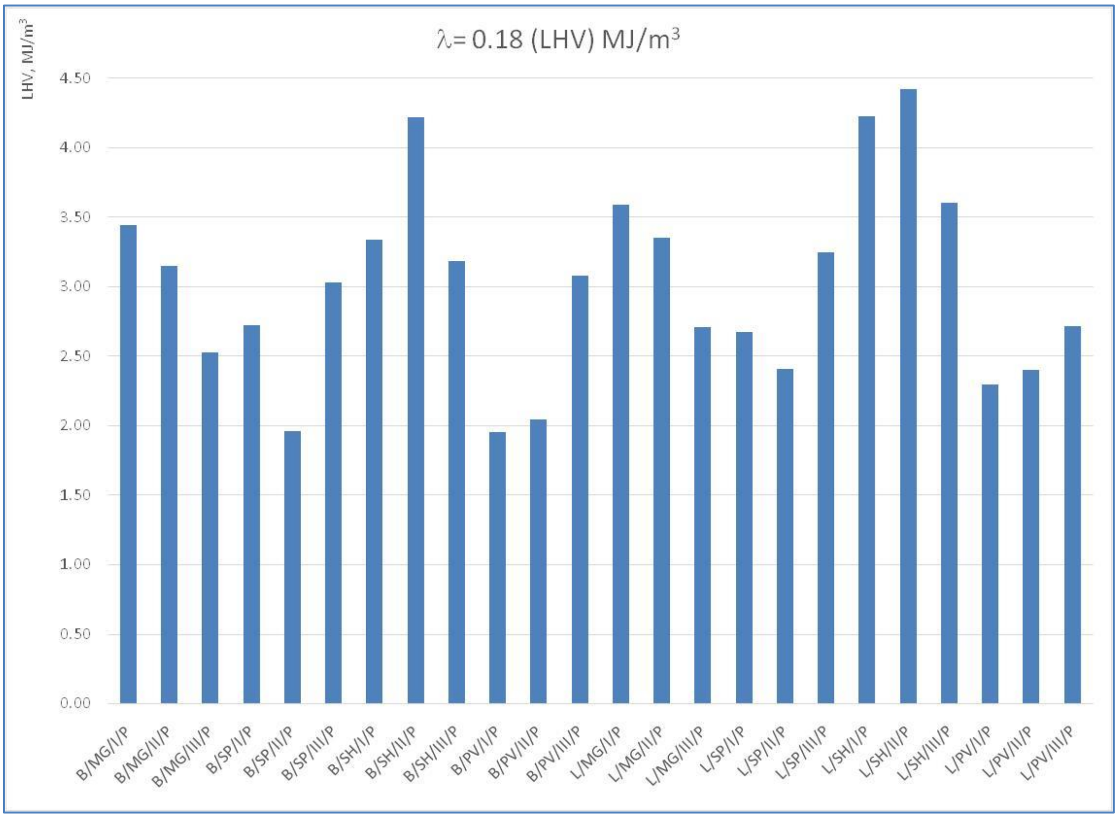
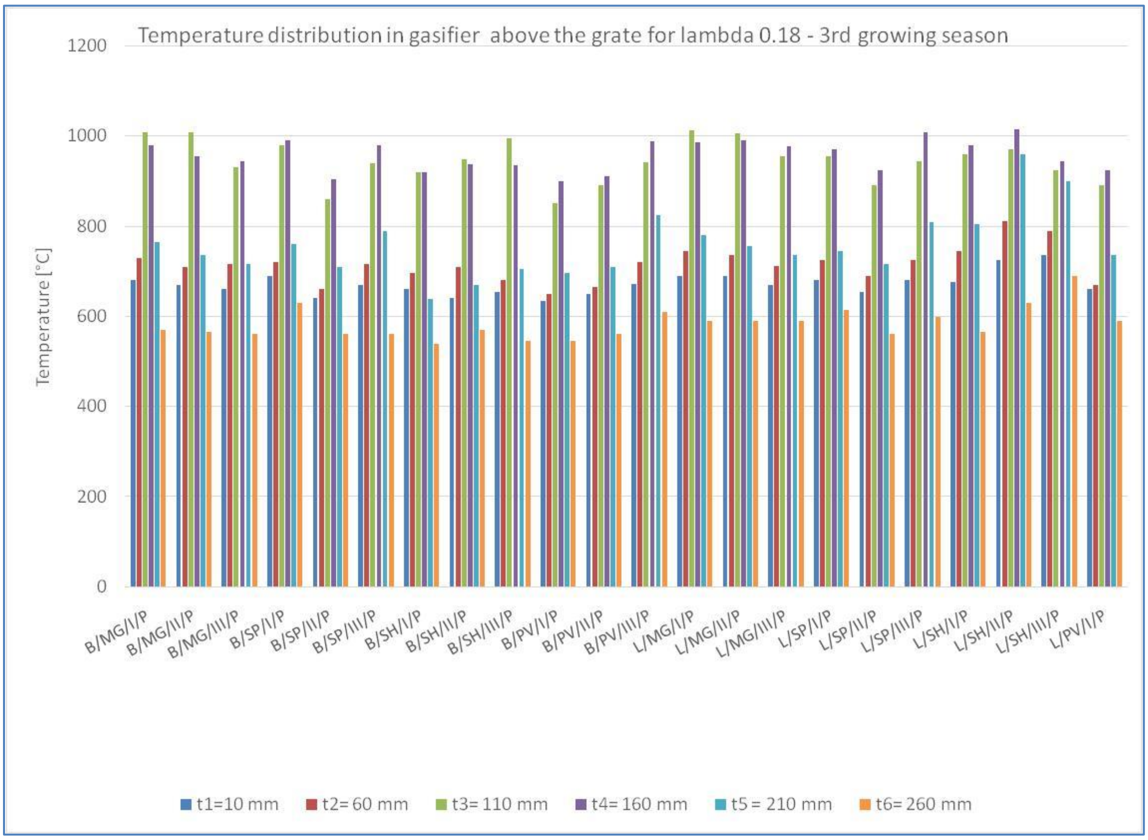


Figure 6 The lower heating value (LHV) all feedstock collected from Bytom and Leipzig new plantations after the third growing season corresponding to λ=0.18



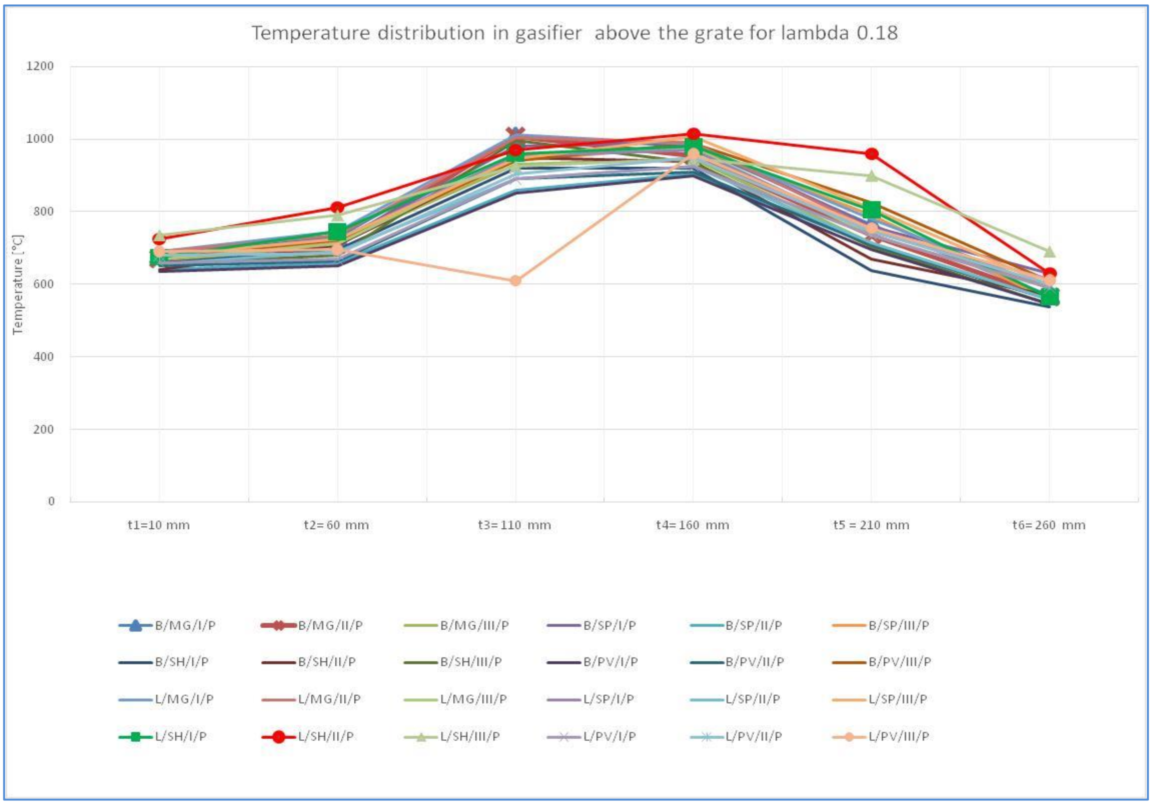


Figure 7 Comparative results of temperature distribution in gasifier above the grate for λ =0.18 after the third growing season corresponding to λ=0.18.

The key findings from the gasification tests performed so far demonstrate that the gasification produces a gaseous fuel, which can be used to produce energy in different types of installations. Produced gas consist mainly CO, CH_4, H_2 and CO_2. The LHV is a little bit more than 4MJ/m^3. This value is acceptable taking into consideration future possibility of the gasification gas utilization in the combustion process.

The effect of inoculum or fertilizer at different type of biomass on LHV has been determined.

For example, in figure 8 are presented the variation of lower heating value for *Sida hermaphrodita treated* with NPK fertilizes in comparison with the same plant type without any treatment. In same time, in Figure 9 is presented *Sida hermaphrodita treated* with inoculum in comparison with plant without any treatment.

Figure 8 Comparative results of the lower heating values for *Sida hermaphrodita* treated with NPK fertilizers and *Sida hermaphrodita* without any treatment

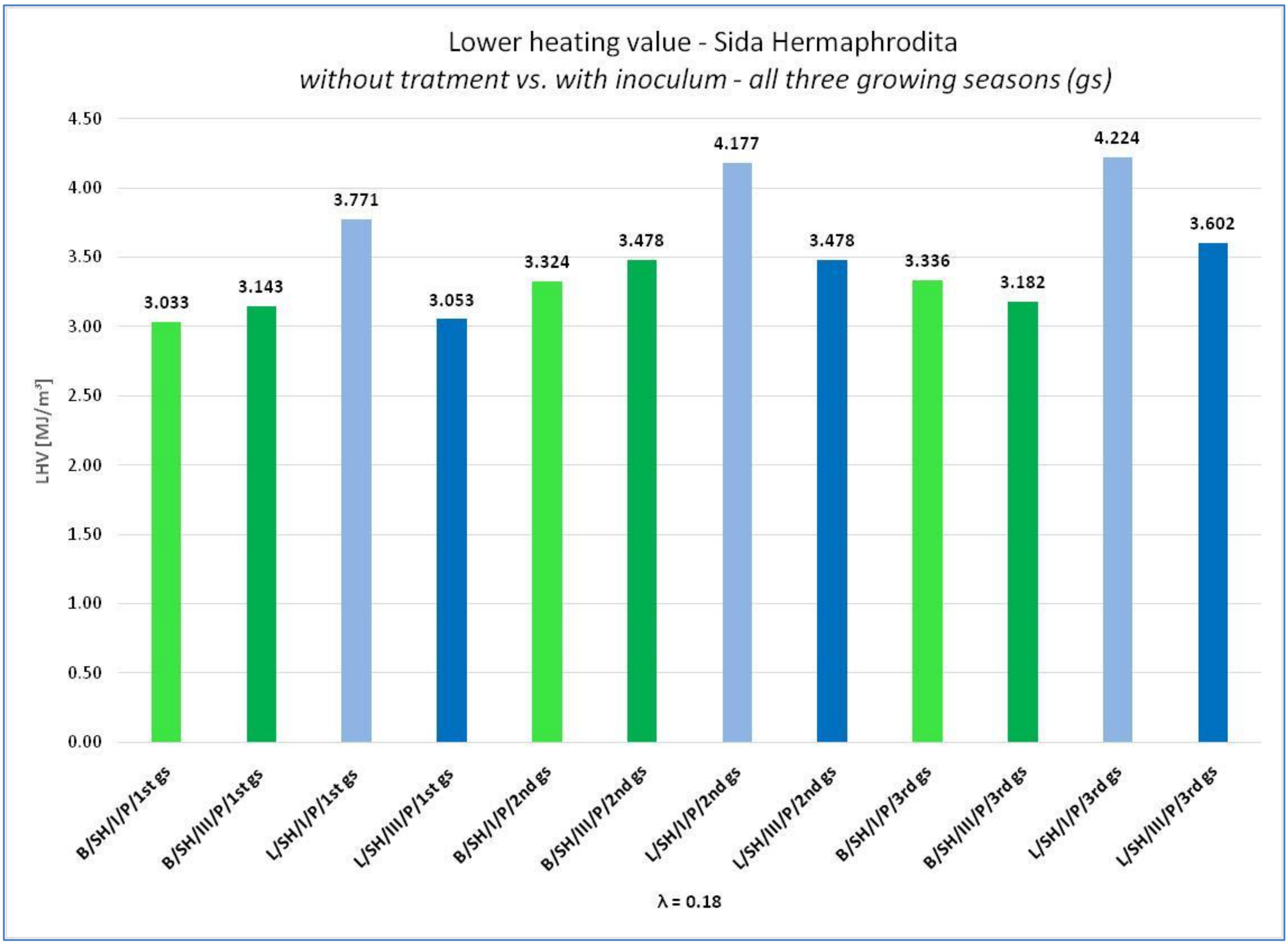


Figure 9 Comparative results of the lower heating values for *Sida hermaphrodita* treated with inoculum and *Sida hermaphrodita* without any treatment

In conclusion, the treatment with NPK fertilizers leads to increase the LHV of *Sida hermaphrodita* harvested from both plantations in comparison with *Sida hermaphrodita* without any treatment. In the other case, the treatment with inoculum in time could lead at a decrease of LHV in both sites.

All detailed results concerning HMC biomass gasification tests overall project period were described in the technical documents presented in TD.3.5-TD 3.8, four separate technical documents detailing the results for the gasification of samples after all growing seasons and all sites (old Bytom plantation, new Bytom and Leipzig plantations).

Identification of areas for process operations improvement

Identification of areas for process operations improvement

During the analysis, palletisation of the heavy metal contaminated energy crop was performed. *Miscanthus* x *giganteus* sample was used. In figure 10 the sample before pelletisation and on Figure 11 – after pelletisation is presented.

Figure 10 *Miscanthus* x *giganteus* before the pelletisation

Figure 11 *Miscanthus* x *giganteus* after the pelletisation

Additionally, the fuel additives to palletization was used. The halloysite was used. Halloysite is an aluminosilicate clay mineral with the empirical formula $Al_2Si_2O_5(OH)_4$. Its main constituents are aluminum (20.90%), silicon (21.76%) and hydrogen (1.56%). However, the chemical composition is subject to little variation. The common presence of impurities (associated clay minerals, Fe oxides or poorly organized minerals, some of which may also be localized within halloysite tubes) in halloysitic samples makes it difficult to assess the chemical composition of the halloysite. It is postulated that due to its catalytic properties, the halloysite can positively influence on the gasification process. On the Figure 12, the pellets of the *Miscanthus* x *giganteus* samples prepared with the 10 % of the dry mass of the halloysite is presented.

Figure 12 ***Miscanthus x giganteus pellets with halloysite***

The influence of the pelletisation and catalyst addition on gasification gas composition is presented on Figures 13, 14.

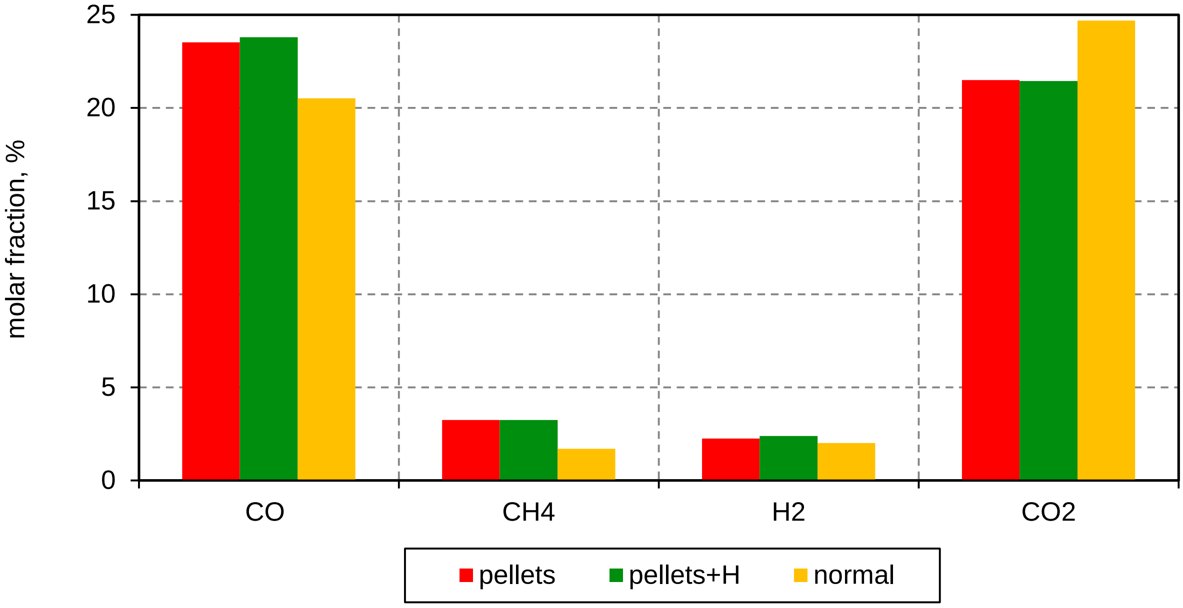


Figure 13 The influence of pelletisation and catalyst addition on gasification gas composition

Analyzing this figure, it can be firstly concluded that pelletisation causes positively on the gas composition. It can be observed that molar fraction of combustible components (carbon monoxide, hydrogen and methane) is higher in the gasification gas achieved from the gasification process of pelletized biomass. This is mainly due to easiest air penetration by the bed in the fixed bed facility during the process in comparison to tests with cut biomass. Similar tendency is observed for pellets wit catalyst. Nevertheless, changes in the compositions are rather small between the gas achieved from pellets gasification and the gasification of pellets with halloysite. So, the influence of the pelletisation and catalyst addition on the Lower Heating Value of the gasification gas is also analyzed.

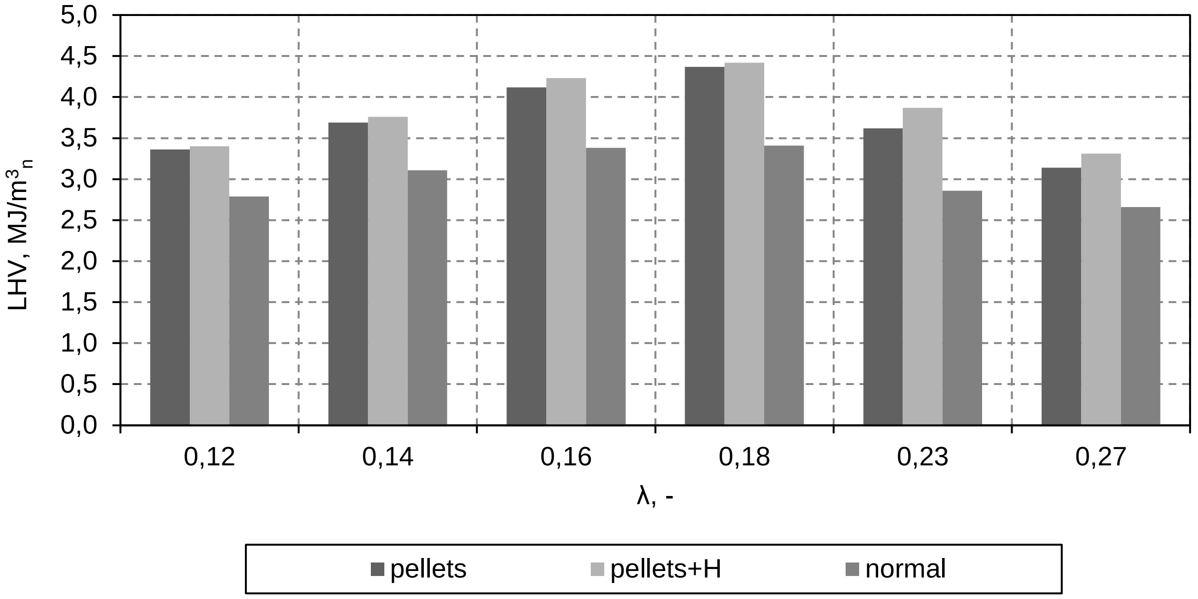


Figure 14 The influence of pelletisation and catalyst addition on the Lower Heating Value of gasification gas

The halloysite addition is especially strong visible on results presented on this Figure. This is mainly due to Fe content in this additive. It is postulated that the metallic iron obtained by reducing the iron oxides (FeO, Fe_2O_4 and Fe_3O_4) as tar breakdown catalysts was utilized in gasification process of biomass influence on the composition of gases produced and the tar content. The gasification gas is characterized by higher content of hydrogen and the amount of tar is significantly lower compared with non-catalytic gasification process of biomass.

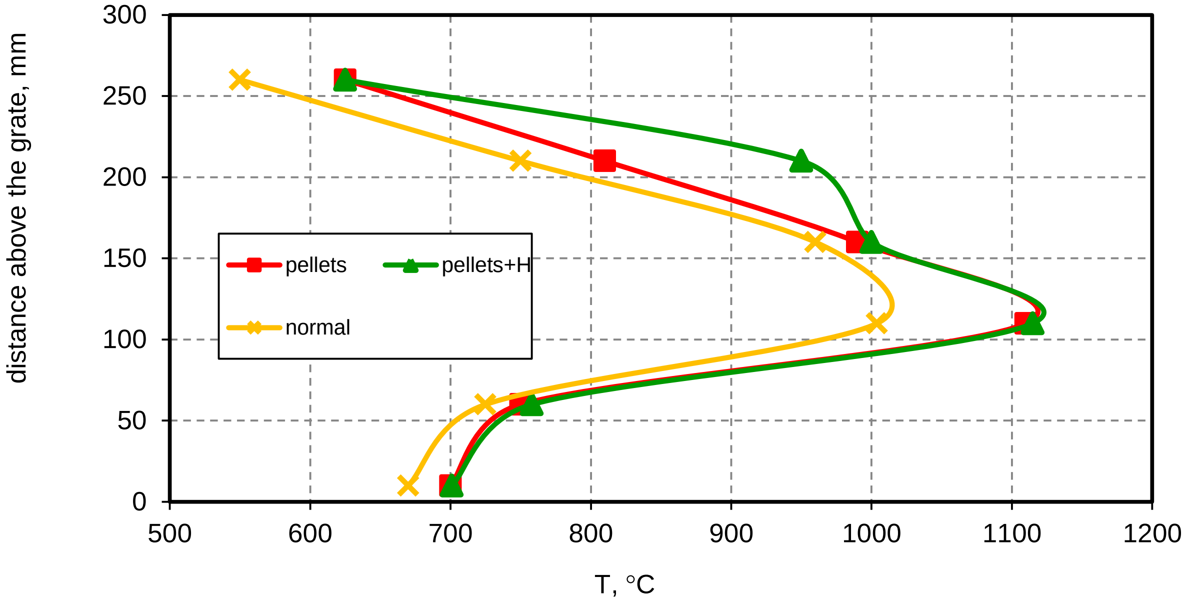


Figure 15 The temperature distribution in the gasification reactor – the influence of the pelletisation and catalyst addition

All, mentioned effects influence on the temperature distribution in the reactor. Better air penetration and catalyst addition influence on the effectiveness of the gasification reaction and thus on the temperature inside the reactor. Analyzing the results presented in Figure 15 it can be concluded that the temperature in the reactor during the pellets wit additive gasification Is higher than in other cases.

The Pb and Zn content in ash taken from the gasification cut Miscanthus, pelletized Miscanthus and pelletized Miscanthus with additives was analysed. Analyzing data presented on the Figure 16 and 17 it can be concluded that additive in the pelletized energy crops promote the migration of heavy metal into the solid phase during the gasification. This is advantageous feature of these additives.

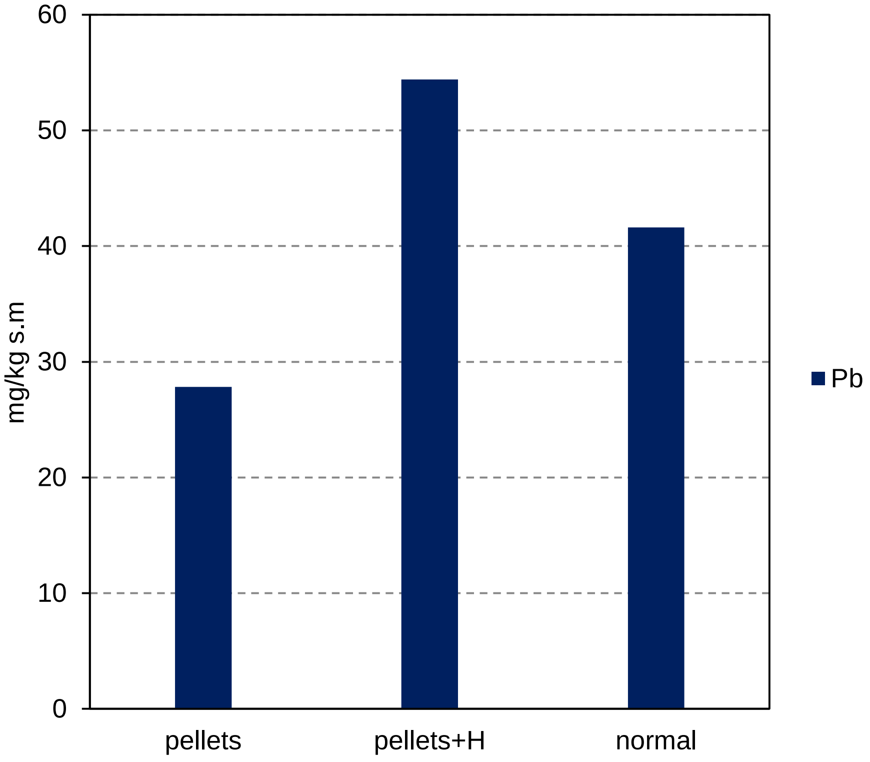


Figure 16 Lead content in the ash after gasification process

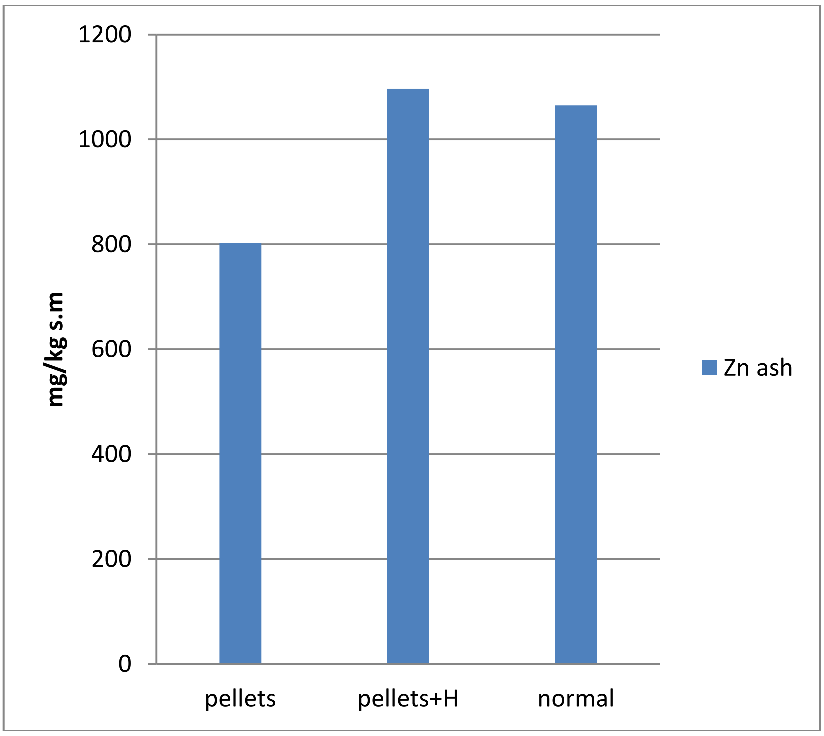


Figure 17 Zinc content in the ash after gasification process

In order to improve the performance of gasifiers, the basic design of the gasifiers is modified. Various improvements on the basic design of the gasifiers have been done and reported by many researchers. Based on those works, the improvement can be classified as shown in Figure 18.

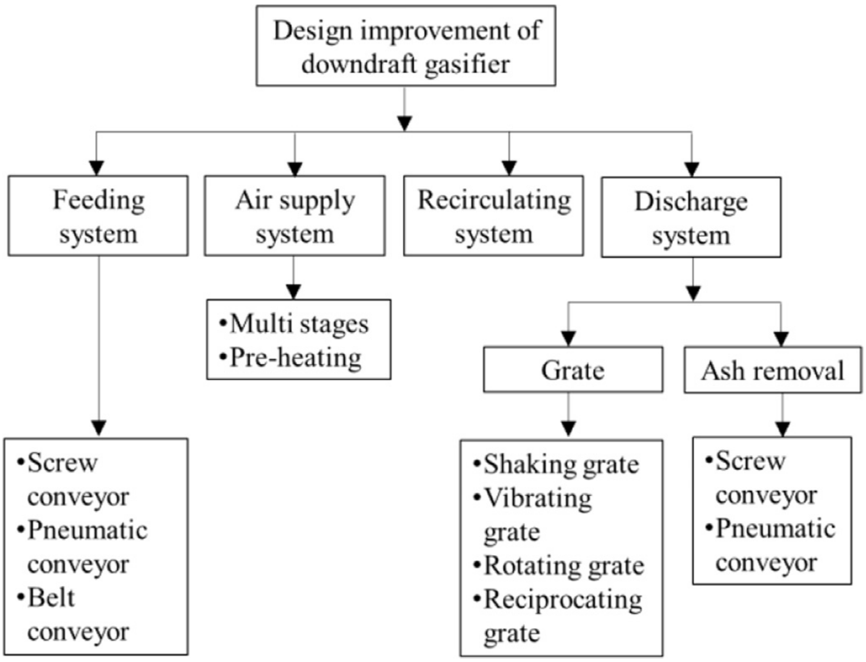


Figure 18 Design improvements of gasifier

The improvements are performed on feeding system, air supply system, producer gas recirculating system, and discharge system. The feeding system is improved with the use of screw, pneumatic, and belt conveyor. The utilization of single-stage and atmospheric air supply are enhanced with the use of multi-stage and heated air supply system, respectively. The recirculating system is employed to utilize producer gas heat for air heating and biomass drying. The improvement work is also performed on the discharge system (grate system and ash disposal system). The grate system is improved with the use of shaking grate, vibrating grate, rotating grate, or reciprocating grate. Ash and char are disposed from the ash pit by a screw or pneumatic conveyor.

Feeding system

In order to extend the batch operation time, fuel hopper is used for feedstock feeder and it is attached on the top of the gasifier. During gasification, the feedstock from hopper flows downward to the gasifier reactor. Feedstock is fed manually in particular interval time during the operation. In more advanced designs, the hopper is located apart from the main reactor. These designs require additional feeding unit for transporting biomass from the hopper to main reactor. The additional feeding unit used can be a screw conveyor [1, 2], a pneumatic conveyor [3], or a belt conveyor [4]. Feedstock feeding rate depends on bed density and rotation speed of the drive motor [1]. The feeding rate can be automated with the use of mechanical level measurement device equipped with laser sensor as developed by [2]. The sensor follows the feedstock level in the gasifier and sends the signal to the drive motor for an ON-OFF position. For a low-density feedstock such as rice husk, the pneumatic conveyor system can be used [3]. The use of the conveyors enables continuous feeding of biomass feedstock from the hopper into the main reactor. However, it needs additional energy input for the motor.

Air supply system

Air as gasification agent is supplied into oxidation zone through air nozzle or tuyer by means of blower or suction fan. The nozzle or tuyer is located perpendicular to the gasifier wall in particular distance above the grate. Multi-stage air supply systems have been developed for enhancing the single stage air supply system.

Galindo et al. [5] reported a downdraft gasifier with two-stage air supply system, 1st stage and 2nd stage. The primary air is supplied at the 1st stage located 300 mm above grate and the secondary air is supplied at the 2nd stage located 400 mm above the primary air. The same gasifier is also used for gasification of Eucalyptus wood residue by [6]. Air ratio is the ratio of air flow rates between the 2nd stage and the 1st stage. Meanwhile, total air is the sum of primary and secondary air flow rates. The application of two stage air supply in gasification of Eucalyptus wood increases pyrolysis temperature as high as oxidation temperature, thus reduces tar content in producer gas [5]. Because the temperature of pyrolysis zone increases, much lighter compounds are formed during feedstock devolatilization in the pyrolysis zone. The compounds are more easily cracked when entering the combustion zone [6].

Other researchers [1, 2, 7, 8] reported gasifier with three-stage air supply system, and [9] informed gasifier with four-stage air system. Reported by [1], 1st stage air is fed through a pipe along the vertical axis of the gasifier, 2nd and 3rd air are injected through nine nozzles around the gasifier circumference. The use of three-stage air supply gives high and uniform temperature in the oxidation and the reduction zones, thus better tar cracking is obtained [1]. As found in Ref. [2], two-stage air (primary and secondary) are injected into the oxidation zone through circumference nozzles and one-stage air (tertiary) is injected into the reduction zone through nozzles in a pipe along the vertical axis of the gasifier. The tertiary air maintains high and uniform temperature in the reduction zone that is useful for tar cracking. The gasifier with three-stage air is reported by [8]. The all three stages air (primary, secondary, and tertiary) are injected through nozzles at the circumference of the gasifier. In order to be operated in three-stage mode, the primary air flow rate should be higher than the secondary air.

The multi-stage air supply is not only used in a closed top gasifier, but also in an open top gasifier, as found in Ref. [8]. Besides provided through three-stage nozzle on circumference of the gasifier, air is also supplied from the open top of the gasifier.

For improving the gasifier performance, heated air is used instead of atmospheric air. The air is heated up prior to being supplied into the gasifier. As been reported, an electric heater [10] and producer gas heat [11, 12] can be used for this purpose. The electric heater is attached on the air supply line, thus unnecessary to modify the main reactor. When producer gas heat is utilized for heating the gasification air, the heating process can occur inside or outside the reactor. An air jacket is used in internal heating process [11] and a heat exchanger is applied in external heating process [12]. The use of the heated air in biomass gasification increases temperature of the drying, pyrolysis, and oxidation zones, but decreases the temperature of the grate section [13]. Besides, the use of heated air improves the quantity and the quality of producer gas, carbon conversion as well as cold gas efficiency [10].

Recirculating system

Another improvement of gasifier design is the attachment of producer gas recirculating system. The system enables to circulate producer gas to the drying zone or to separate fuel hopper. The circulation aims to utilize producer gas heat for drying the feedstock. Indirect contact occurs between producer gas and feedstock in the drying zone [14] and the same occurs in the apart fuel hopper [15]. Besides the benefit for fuel drying, the system also gives an advantage in cooling of producer gas before leaving the gasifier. The cooling improves the gasifier-engine system when the producer gas is utilized for engine fuel [14].

Discharge system

The discharge system consists of grate system and ash-char disposal system. Basically, the grate has a function of feedstock holder in a reactor during gasification and as a passage for ash and char which flow downward to ash pit. The ash and char are disposed from the ash pit by the removal system. Recent developments, some grate types are shaking grate [14, 16, 17] vibrating grate [5], rotating grate [18], and reciprocating grate [19]. These developments aim to avoid bridging and channeling of low density feedstock during gasification. In shaking grates, a lever is attached on the grate. The grate movement is done by shaking the lever. In vibrating grates, the grate vibrates in particular period of time caused by a vibrator unit. Meanwhile, electric motor is used to rotate the grate in the rotating grate type. Furthermore, the reciprocating grates are designed in such a way enable to move perpendicular to a vertical axis of the gasifier. After a reduction process, the ash and char flow downward through the grate and are disposed from ash and char box. Ash and char are disposed from the box manually or by means of more improved system, such as a screw discharge conveyor [2, 20] or a pneumatic discharge conveyor [1]. The improved system requires additional installation cost for conveyor and driver motor and also operational cost for electricity.

CONCLUSIONS

Pelletisation causes positively on the gas composition. It can be observed that molar fraction of combustible components (carbon monoxide, hydrogen and methane) is higher in the gasification gas achieved from the gasification process of pelletized biomass. This is mainly due to easiest air penetration by the bed in the fixed bed facility during the process in comparison to tests with cut biomass. Similar tendency is observed for pellets wit catalyst. Nevertheless, changes in the compositions are rather small between the gas achieved from pellets gasification and the gasification of pellets with halloysite.

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