

MUNICIPAL SOLID WASTE GASIFICATION WITHIN WASTE-TO-ENERGY PROCESSING

MAREK BALAS, MARTIN LISY, PETR KRACIK, JIRI POSPISIL

Brno University of Technology, Faculty of Mechanical
Engineering, Energy Institute, Brno, Czech Republic

DOI: 10.17973/MMSJ.2017_03_2016137

e-mail: marek.balas@vutbr.cz

This paper discusses theoretical assets and liabilities of a use of advanced thermal technologies within waste-to-energy (WTE) processing. Gasification and pyrolysis are compared to conventional incineration. Major part of the paper deals with results of gasification experiments: various wastes were gasified within a fluid generator with a circulating fluidized bed. The results were later compared. Lower heating value, composition of the syngas and amount of tar within the syngas were the important observed factors. Experiments were performed at a Biofluid, the pilot facility at the Faculty of Mechanical Engineering in Brno.

KEY WORDS

municipal solid waste, gasification, pyrolysis, waste-to-energy

1 INTRODUCTION

Purpose of physical and chemical waste processing is to recycle the materials, produce secondary materials or energy, eliminate or decrease waste toxicity, decrease the hazardous potential of waste, and minimize the waste volume [Beniak 2015]. Some of the waste may be processed directly in a place of its producers; however, hazardous chemical waste, especially complicated mixtures, must be treated in specialized processing facilities. Czech legislation considers the following methods to constitute thermal waste processing: waste oxidation and other thermic processing of waste including incineration of produced matter that leads to higher level of pollution compared to incineration of the same amount of natural gas with similar energy content. Waste production is ever rising and therefore it is wise to focus on development of technologies for its secondary exploitation. This measure will greatly decrease the share of landfilled waste and negative environmental impact. Capacity of WTE plants may be to a certain degree increased. As mentioned above, in addition to waste incineration technologies we may further take advantage of pyrolysis and gasification (especially in fluid reactors). These methods are generally termed "Alternative Conversion Technologies". The so called oxy-fuel combustion also falls within this category [Hrdlicka 2016].

Biomass gasification has witnessed a significant progress within the last 20 years. However, other types of waste have recently been commonly used; these include municipal solid waste (MSW), biodegradable waste and the so called alternative fuels from waste.

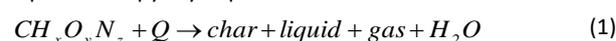
2 WASTE CONVERSION TECHNOLOGIES

Pyrolysis and gasification are, just as incineration, thermal processes of waste decomposition that take place under high temperatures. However, the main difference between incineration on one side and gasification and pyrolysis on the other is the fact that waste is not a fuel to be used but serves as

a material for chemical conversion under high temperatures. There are other thermochemical processes of waste treatment, such as torrefaction and hydrothermal carbonization; however, they are suitable for processing of biodegradable waste and their application in common waste treatment is scarce.

2.1 Pyrolysis

Pyrolysis is an endothermic process of fuel decomposition in the absence of oxygen. Pyrolysis consists of rapid heating and short evaporation of gaseous products (under 1 sec). The final product is a pyrolysis tar (bio-oil, wood bio-oil), a brown liquid with a density of 1.2 kg.m⁻³. Heat necessary for the thermochemical conversion must be supplied from an external source. Thanks to a high share of volatile combustibles, pyrolysis of waste is rather simple. Bio-oil may be applied as a fuel in diesel engines, microturbines, and cogeneration units. The following is an equation for pyrolysis process:

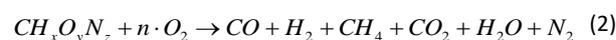


Temperature of fuel decomposition is the main indicator within this process. The temperature defines a share of all the three products and their quality. Pyrolysis typically occurs within temperatures of 500–550 °C; some technologies apply higher temperatures, which results in production of gas and not pyrolysis tar. Pyrolysis occurring within temperatures of ca. 500 °C produces gas with lower heating value of 15–19 MJ.m⁻³ and pyrolysis tar with lower heating value of 27 MJ.kg⁻¹. As the temperature rises, share of produced gas rises too to the detriment of char and pyrolysis tar production. Higher heating value of the gas rises with rising temperature and time; in contrast, higher heating value of char drops [Lopez 2011].

Compared to incineration, pyrolysis decreases or even prevents corrosion and emissions by capturing alkali and heavy metals (with the exception of mercury and cadmium), sulphur and chlorine within the solid residue contents; pyrolysis further prevents formation of large amounts of NO_x [Chen 2015]. However, most of PCDD/F is within the pyrolysis tar [Weber 2001]. Some studies claim that pyrolysis does not reduce the formation of PCDD/F [Mohr 1997].

2.2 Gasification

Gasification is a complex thermal and chemical conversion of organic matter within conditions of oxygen deficiency into a lower heating value (LHV) gas (4 MJ.m⁻³ to 15 MJ.m⁻³) consisting of a series of simple reactions. The following is an equation for gasification process



The process occurs at higher temperatures, typically between 750 °C and 950 °C. The product of the process of gasification is syngas, the main constituents of which are CO, CO₂, H₂, CH₄, higher hydrocarbons, N₂, and impurities. The main focus at the syngas is on its quality (heating value, composition) and quantity generated during gasification - plus amount and composition of impurities within. The produced syngas is one of the assets of gasification compared to incineration. The syngas does not necessarily serve for heat production as is common for direct combustion; the syngas has several application potentials, for example in chemical industry. The syngas may obviously be directly combusted, which provides all the advantages of syngas combustion as opposed to incineration of a heterogeneous solid fuel. Combustion of the syngas within a cogeneration unit or in an integrated steam-gas cycle means use of a fuel with efficiency that is higher than that of direct incineration. Waste gasification applications may have much lower capacity than large central CHP plant.

	Ebara TwinRec	Entech Renew. Energy Techologies	InEnTec	INEOS Bio	International Environ. Solutions	Mitsui Recycling 21	Nippon Steel DMS	Plasco Energy	Regulation No. 415/2012 Sb.
Territory	Kawaguchi Japan	Kuznica Poland	Richland USA	Fayetteville USA	Romoland, USA	Toyohashi Japan	Kazusa, Japan	Ottawa, Canada	
Technol.	Fluid bed Gasif.	Gasif.	Plasma Arc Gasif.	Gasif.	Pyrolysis	Pyrolysis Gasif.	Gasif.	Plasma Arc Gasif.	
Input	420 tpd MSW	3.5 tpd medical waste	10 tpd	1.5 tpd MSW	30 tpd MSW	400 tpd MSW	200 tpd MSW	110 tpd MSW	
Output	5.5 MWe					8.7 MWe	2.3 MWe		
Emission [mg.m⁻³]									
PM	<1.7	0.98	3.3	2	5.75	<1.0	14.1	12.8	10
HCL	<2.8	7.9	2.7			55.8	<12.5	3.1	10
NO_x	41	254	162	10	129	82.8	31.2	150	400/200
SO_x	<4	51.9			0.44	25.9	<21.9	26	50
Hg	<0.007	0.008	0.0002	0.0001				0.0002	0.05
PCDD/F	0.000072	0.028	0.0067	0.003	0.00058	0.0045	0.045	0.0093	0.01
ref O ₂ 7 %									ref O ₂ 11 %

Table 1. Emissions from a waste gasification plant [Lamers 2013]

Some of the disadvantages of this technology include establishment of a complex and therefore expensive facility, increase in safety regulations for dealing with combustible gas, and requirements on elimination of impurities produced in the syngas by the gasification process. The content of impurities in the syngas causes operation problems to the units due to clogging and tarring of working surfaces of engines and turbines, which may even lead to serious damage to the equipment under operation. Impurities include dust most of all (airborne solids), alkali compounds, nitrogen compounds, sulphur compounds, compounds of chlorine and fluorine, and tar. Tar and dust are the main factors limiting the use of syngas [Lisy 2012]. Gasification of waste may convert ca. 71 % of the energy from the fuel into the syngas [Begum 2014].

Gasification of MSW faces several difficulties. MSW is a less homogenous fuel than biomass. The syngas further has a high share of incombustible mixtures, and therefore has a lower LHV (ca. 3.5 MJ.m⁻³) compared to syngas from gasification of pure biomass. Conversion ratio of carbon is ca. 70 %; conversion ratio of carbon within solid biofuel burning at identical conditions is more than 90 %. Tar concentrations, on the other hand, are comparable [Campoy 2014], [Xiao 2009]. Gasification of kitchen waste with oxygen only produces syngas with double the LHV: ca. 7–8 MJ.m⁻³ [Niu 2014]. Application of CO₂ as a moderator is interesting [Pohorely 2014].

Comparison of gasification and incineration proves that efficiency of energy conversion is higher within gasification than within incineration [Girods 2009].

In addition, formation and reformation of toxic dioxins and furans (especially from PVC) is another difficulty related to incineration of MSW. There are three ways these toxins can be present within flue gas:

- By decomposition, as smaller parts of larger molecules;
- By “reforming” when smaller molecules combine together; and/or
- By simply passing through the incinerator without change.

Incineration does not allow control of these processes, and all clean-up occurs after combustion. One of the important advantages of gasification is that the syngas can be cleaned of contaminants prior to its use, eliminating many of the types of after-the-fact (post-combustion) emission control systems

required by incineration plants. The clean syngas can be used within reciprocating engines or turbines to generate electricity or further processed to produce hydrogen, substitute natural gas, chemicals, fertilizers or transportation fuels, such as ethanol [Gasification 2014].

Gasification is significantly different from and cleaner than incineration [Gasification 2014]:

- At the high temperature environment in gasification, larger molecules such as plastics, are completely broken down into the components of syngas, which can be cleaned and processed before any further use;
- Dioxins and furans need sufficient oxygen to form or reform, and the oxygen-deficient atmosphere in a gasifier does not provide the environment needed for dioxins and furans to form or reform;
- Dioxins need fine metal particulates in the exhaust to reform; syngas from gasification is typically cleaned of particulates before being used.

Decrease in dioxins and furans emissions via gasification has been verified by various studies. [Lopes 2015] researched dioxins and furans generation during gasification of MSW within a horizontal chamber with a moving grate. Amount of dioxins within the gas reached a maximum of 0.45 ng.m⁻³. Amount of dioxins measured within the same fuel that has been directly incinerated ranged from 44 to 11 ng.m⁻³. Another study presents dioxin levels from the gasification ranging from 0.04 to 0.06 ng.m⁻³ [Kawamoto 2015].

Reducing environment within the gasifier significantly suppresses not only dioxins and furans formation but also formation of other impurities [Arena 2012].

Waste gasification plants are therefore destined to become environmentally-friendly technology for waste treatment.

3 EXPERIMENTAL

3.1 Material

Waste is an energy carrier with a rather high calorific value, but the element composition, water content and overall structure varies significantly. Waste consists of a large portion of ash content (ash, debris, soil, etc.) and hazardous substances. Actual composition of municipal waste further differs in relation to a place of its origin. Composition fluctuates in relation to the collection site (areas with apartment houses, suburban areas, and small municipalities)

and season of the year. General energy characteristics of municipal waste are defined in literature [Balas 2014], [Krizan 2011]

The research team tested modified MSW. Modification consisted of separating the metal parts, and grinding the fuel to a maximal size of 3 cm. The feedstock thus became very homogenous and could be fed to Biofluid 2. Three feedstocks have been selected for the experiments: pure MSW, mixture of MSW and wood chips (1:1), and pure biomass for a comparison (wood chips from coniferous trees). Basic analysis was conducted for these feedstocks, preliminary analysis of the feedstocks, lower heating value, element analysis of the feedstocks, and element analysis of the ash content; a softening point of the ash in a reducing environment was defined. Analysis results are given in Tab. 2.

	Municipal solid waste	MSW and wood chips mixture	Wood chips from spruce
	[%wt]	[%wt]	[%wt]
Volatile substances	80.1	77.5	74.1
Bound carbon	13	13.6	14.5
Noncombustible substances	5.4	3.3	0.5
Huminiti	1.5	5.6	11
C	46.6	45.7	44.6
H	7.6	6.7	5.5
O	36.9	37.5	38.4
N	1.2	0.7	0.1
Total S	0.2	0.1	0
Total Cl	0.7	0.4	0
CaO	1.3	19.4	43.5
SiO ₂	1.5	4.5	8.5
Al ₂ O ₃	1.1	1.8	2.7
TiO ₂		0.1	0.2
Cd Cr	< 30		0
Cr	36	20.6	0.1
Hg	1	0.6	0
Pb	200	114	0
As	<30	ND	ND
Se	<50	ND	ND
LHV [MJ.kg ⁻¹]	33	25.8	16.4
Melting point [°C]	1,138	1,138	1,257

Table 2. Feedstock properties

3.2 Experimental Unit

Experiments are carried out at fluidised bed atmospheric gasifier with stationary fluidized bed called Biofluid 100 (Fig. 1). Process temperature control is carried out by changing the fuel to air ratio with temperature control range being within the 750 °C to 900 °C brackets. Average heating value of the produced gas ranges from 4 MJ.m⁻³ to 7 MJ.m⁻³, depending on feedstock used and operating conditions.

Feedstock comes from rake-equipped storage tank to be fed to the gasifier in batches by worm conveyor. Blower-compressed air is delivered to the gasifier, to under its grate, as primary air ensuring partial oxidization of fuel and maintaining the fluidized bed. Moreover, air can be supplied at two other levels as secondary air and tertiary air. Ash from the gasifier is discharged to ashbin on intermittent basis by

means of a purpose-designed special moving grate. A more detailed description is given in, e.g. [Lisy 2009].

The parameters of the gasifier are as follows:

- Output (in generated gas) 100 kW_t
- Fuel consumption max. 40 kg.h⁻¹
- Air flow max. 150 m³.h⁻¹



Figure 1. Atmospheric fluidized bed gasifier Biofluid design

3.3 Test Procedure and Operating Conditions

Cornerstone of the measurement is to analyse composition of the gas and content of the tar in relation to the operating parameters. Gas quality measurement is usually carried out in two ways. In order to evaluate the exact gas composition, off-line samples into glass sample containers and subsequent analysis using a gas chromatograph are employed. This method provides for accurate analysis of the gas content: N₂, O₂, CO, CO₂, H₂, CH₄ and other low carbohydrates. On-line analysis allows for monitoring of O₂, CO, CO₂ and H₂. However, accuracy of on-line analysis is inferior to the off-line one, and this method is usually employed for control of the gasification process.

Tar sampling is carried out in line with IEA methodology by capturing tar in a solution that is subsequently analysed by gas chromatograph with mass spectrometer [van Paasen 2002].

Operating parameters are monitored during operation and continuously recorded by the control computer. They include, in particular, mass flow of fuel, temperatures at various points of the unit, pressure difference in the fluidized bed, gas flow and pressure losses, and the temperature and air flow. A more detailed description is given in, e.g. [Skoblia 2004].

All the given values of gas and tar composition are average values of at least five samples. Sample analysis was performed at the Institute of Chemical Technology in Prague.

4 EXPERIMENTAL RESULTS AND DISCUSSION

Following chapters discuss results of atmospheric gasification of MSW, mixture of MSW and wood chips, and pure wood chips as feedstocks.

4.1 Operational Stability

Our facility has so far had experience with gasification of wood biomass in the form of pellets, saw-dust, wood scobs and wood chips, and stalk in the form of pellets and chopped straw. Operations of MSW compare to none of the above. Stable supply of a required amount of feedstock is a crucial prerequisite for stable operations of this gasifier. The last one has proved to be rather difficult in case of MSW. Stable operations were difficult to regulate, despite the fact that the feedstock had been homogenized, as discussed above. After several failed attempts, a stable regime that lasted for several hours was achieved. This amount of time was enough to sample the gas and tar. In addition to continuous supply of feedstock, sintering of the material in the bed proved to be another problem. Although the melting point of the MSW ash content was defined in certified laboratories and equalled more than 1,100 °C, sintering of ash was one of the few limiting factors that impeded the research team from reaching the optimum operating conditions. The aim was to reach operating temperature within 800–830 °C, but this was never achieved for MSW, and the mixture of MSW and wood chips. After several failed experiments, the team defined a safe operating temperature of 750 °C for MSW, and 780 °C for the mixture of MSW and wood chips. Higher temperatures caused unstable operations and fusing of the material. Results were compared to experiments with pure wood chips gasified at 780 °C and 820 °C, which is the optimum temperature for gasification of dendromass. Extraction of the ash posed another difficulty since MSW produced much more ash than biomass, and the facility has not been designed to comply with it. Gasification equivalence ratio (ER) was maintained during all measurements between 0.3–0.4. Gas and tar samples were taken once the operations were stable. The stable operations were maintained for 4–6 hours.

4.2 Syngas Composition

Average values of the syngas composition for all three fuels are given in the Tab. 3.

It is quite obvious at first glance that the share of hydrocarbons in the syngas from gasification of MSW and mixture of MSW and wood chips is higher. Hydrocarbons in the syngas from these two feedstocks reach ca. 12 %; hydrocarbons in the syngas from wood chips reach ca. 3 %. Higher share of hydrocarbons is a logical consequence of the feedstock composition which is predominantly made up from polymeric C-H-O chains. Closer observation reveals that the syngas contains a higher share of heavy hydrocarbons; difference in methane content was not that significant. Detailed share of hydrocarbons is illustrated in Fig. 2. Hydrogen content is also distinct.

		MSW	MSW + wood chips	wood chips (780 °C)	wood chips (820 °C)
CO ₂	%wt	11.19	12.66	19.19	17.58
H ₂	%wt	4.61	6.38	13.69	13.79
CO	%wt	7.84	12.05	7.28	10.59
N ₂	%wt	63.51	57.25	56.24	54.11
CH ₄	%wt	4.44	4.50	2.09	2.41
C ₂ H ₄	%wt	4.29	3.33	0.62	0.65
Other C _x H _y	%wt	3.36	3.02	0.22	0.23

Table 3. Syngas composition

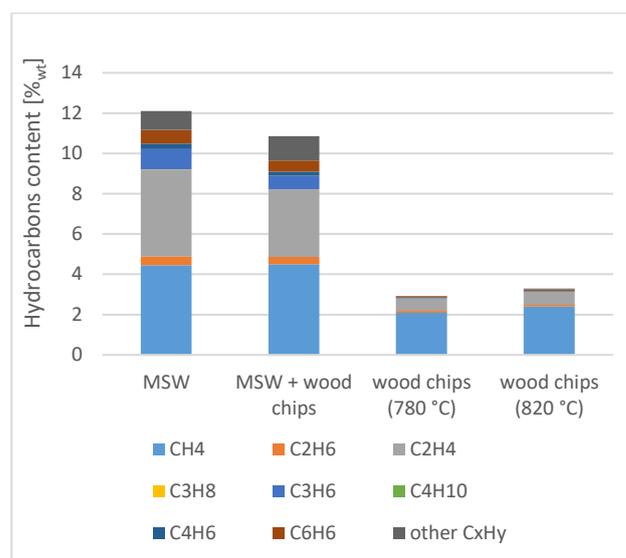


Figure 2. Detailed content of hydrocarbons detected in the syngas

Increased amounts of hydrocarbons further lead to increased higher heating value of the syngas from the two fuels, see the OBR. The results were basically similar for both types of fuels that is pure MSW and mixture of MSW and wood chips. We may therefore assume that the lower gasification temperature must have a significant impact and so do the metalation reactions. Syngas from the other fuels, that is wood, has similar composition as well as HHV.

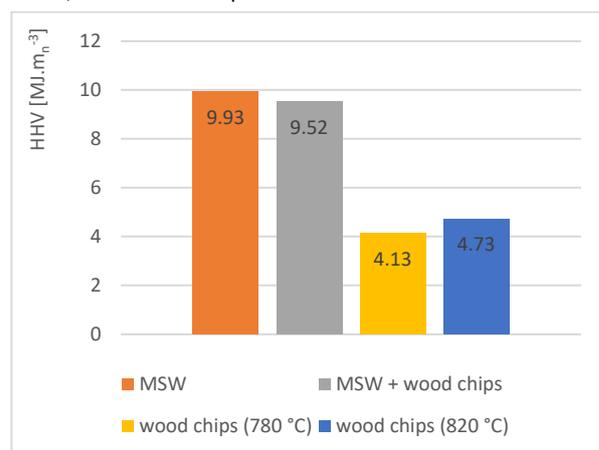


Figure 3. Higher heating value of the syngas

4.3 Tar Composition

More profound differences may be observed in the amount and composition of tar, see Fig. 4. The chart presents total tar content in the syngas and presence of dominant tar classes according to the ECN classification based on condensation and solubility of particular tar components in water [Kiel 2004]. Class 2 includes especially heterocyclic components (such as pyridine, phenol, cresol, quinoline); class 4 includes light polyaromatic hydrocarbons (such as naphthalene, biphenyl, fluorene, anthracene, phenanthrene); class 5 includes heavy polyaromatic hydrocarbons (such as fluoranthene, pyrene, benzo-anthracene, perylene, Indeno-pyrene).

Dominant class in materials from separated waste is Class 4 that is light polyaromatic hydrocarbons (PAH). These conclusions are further substantiated by operating temperatures which are crucial for production of the so called secondary tar; the temperatures are close to production of tertiary tar [Milne 1998]. Chart no 3 clearly shows that tar

content in the syngas from waste gasification ($11\text{--}13\text{ g.m.n}^{-3}$) is higher by several orders that in syngas from pure biomass gasification. With respect to existing tar limits in combustion engines ($50\text{--}100\text{ mg.m.n}^{-3}$), the syngas is not suitable for any further applications, unless it is purified. The only acceptable application is direct combustion. Technical and energy requirements of subsequent tar elimination have a major negative impact on economics and profitability of the facility. Therefore it is advisable to find plants suitable for direct application of the syngas, such as lime production plants and cement plants; or as a substitute for fossil fuels in steam boilers.



Figure 4. Tar content within the syngas and tar classification

5 CONCLUSION

Purpose of this paper was to present basic knowledge from fluid gasification of MSW and draw attention to assets and advantages of the technology and its potential applications in thermal waste processing. Results prove that the tested materials are suitable for fluid gasification. However, design of a gasification reactor must be adequately adjusted and subsequent application of the syngas carefully considered. Main observations and conclusions of the experiments:

- MSW is a complex feedstock and must be pre-modified, that is homogenized and the amount of metals and other solid non-combustible substances must be reduced.
- Supply of the feedstock into the gasification reactor must be closely monitored so that the feedstock flow into the reactor is as even as possible; the control features should also allow for precise regulation. The same applies to extraction of the ash.
- Results of syngas and tar composition prove that the gasification temperature should be higher or the retention time should be longer so that all necessary gasification reactions may take place. This measure could reduce the amount of tar and heavy hydrocarbons within the syngas, and increase the amount of hydrogen.

High tar concentrations in waste incineration are a major impediment to use of the syngas within combustion engines and turbines. Issues related to syngas cleaning are the main reason why many projects for biomass and waste gasification have failed.

Future research should focus on monitoring of other pollutants, such as dioxins, furans and chlorine compounds. Transfer of heavy metals into the syngas should also be

closely monitored and analysed. However, produced pollutants must be observed not within the produced syngas but within the final product, that is the flue gas from application of the syngas in a specific power technology. These are the values that may be later compared to valid legislation or emissions from conventional waste incinerators.

ACKNOWLEDGEMENT

This work is an output of research and scientific activities of NETME CENTRE PLUS (LO1202) by financial means from the Ministry of Education, Youth and Sports under the „National Sustainability Programme I“.

REFERENCES

- [Arena 2012] Arena, U. Process and technological aspects of municipal solid waste gasification. A review, *Waste Management* 32 (2012) 625–639, ISSN 0956-053X
- [Balas 2014] Balas, M., Lisy, M., Skala, Z. Waste incineration plants - waste as a fuel (in Czech) TZB- info, 2014, No. 43, pp. 1-8. ISSN: 1801- 4399
- [Beniak 2015] Beniak, J., Krizan, P., Matus, M.: A comparison of the tensile strength of plastic parts produced by a fused deposition modeling device (2015) *Acta Polytechnica*, 55 (6), pp. 359-365 ISSN 1210-2709
- [Begum, 2014] Begum, S., Rasul, M.G., Cork D. and Akbar, D. An experimental investigation of solid waste gasification using a large pilot scale waste to energy plant, *Procedia Engineering* 90 (2014) 718 – 724
- [Campoy, 2014] Campoy, M., Gomez-Barea, A., Ollero, P., Nilsson, S. Gasification of wastes in a pilot fluidized bed gasifier, *Fuel Processing Technology* 121 (2014) 63–69
- [Gasification 2014] The Waste-to-Energy Solution, Gasification Technologies Council, date of citinyg 28.6.2015, Available from http://www.gasification.org/uploads/downloads/GTC_Waste_to_Energy.pdf
- [Girods 2009] Girods, P., Dufour, A., Rogaume, Y., Rogaume, C., Zoulalian, A. Comparison of gasification and pyrolysis of thermal pre-treated wood board waste, *Journal of Analytical and Applied Pyrolysis*, Volume 85, Issues 1–2, May 2009, Pages 171-183, ISSN 0165-2370
- [Hrdlicka 2016] Hrdlicka, J., Skopec, P., Opatril, J., Dlouhy, T. Oxyfuel combustion in a bubbling fluidized bed combustor. Paper presented at the Energy Procedia, 2016, 86 116-123.
- [Chen 2015] Chen, D., Yin, L., Wang, H., He, P. Reprint of: Pyrolysis technologies for municipal solid waste: A review, *Waste Management*, Volume 37, March 2015, Pages 116-136, ISSN 0956-053X
- [Kawamoto 2015] Kawamoto, K., Miyata, H. Dioxin formation and control in a gasification–melting plant. *Environ Sci Pollut Res* (2015) 22:14621–14628, ISSN 0944-1344
- [Kiel 2004] Kiel, J.H.A., van Paasen, S.V.B., Neeft, J.P.A. et al. Primary measures to reduce tar formation in fluidised-bed biomass gasifier, Final report SDE project P1999-012, ECN C 04 014, (March 2004)
- [Krizan 2011] Krizan, P. et al. Briquetting of municipal solid waste by different technologies in order to evaluate its quality and properties (2011) *Agronomy Research*, 9 (SPPL. ISS. 1), pp. 115-123.
- [Lamers 2013] Lamers, F., Fleck, E., Pelloni, L., Kamuk, B. *Alternative Waste Conversion Technologies. ISWA 2013*
- [Lisy 2009] Lisy, M. et al. Research into biomass and waste gasification in atmospheric fluidized bed (2009) *Proceedings of the 3rd WSEAS International Conference on Energy Planning, Energy Saving, Environmental Education, EPESE '09*,

Renewable Energy Sources, RES '09, Waste Management, WWAI '09, pp. 363-368.

[Lisy 2012] Lisy, M. et al. Biomass gasification - primary methods for eliminating tar (2012) Acta Polytechnica, 52 (3), pp. 66-70., ISSN 1210-2709

[Lopes 2015] Lopes, E.J., Okamura L.A. and Yamamoto, C.I. Formation of dioxins and furans during municipal solid waste gasification. Brazilian Journal of Chemical Engineering Vol. 32, No. 01, pp. 87 - 97, January - March, 2015 ISSN 0104-6632

[Lopez 2011] Lopez, A., et al. Influence of time and temperature on pyrolysis of plastic wastes in a semi-batch reactor, Chemical Engineering Journal, Volume 173, Issue 1, 1 September 2011, Pages 62-71, ISSN 1385-8947

[Milne 1998] Milne T.A., Evans R.J, Abatzoglou N. Biomass Gasifier „Tars“: Their Nature, Formation and Conversion, NREL/TP-570-25357, Colorado,USA, (1998).

[Mohr 1997] Mohr, K., Nonn, C., Jager, J. Behavior of PCDD/F under pyrolysis conditions, Chemosphere, 34 (1997), pp. 1053–1064

[Niu 2014] Niu, M., Huang, Y., Jin, B., Wang, X. Oxygen Gasification of Municipal Solid Waste in a Fixed-bed Gasifier, Chinese Journal of Chemical Engineering, Volume 22, Issue 9, September 2014, Pages 1021-1026, ISSN 1004-9541

[Pohorely 2014] Pohorely M. et al. CO₂ as Moderator for Biomass Gasification. (Eng) Fuel 117(Part A), 198-205 (2014)

[Skoblia 2004] Skoblia, S. Modification of the composition of gas from biomass gasification (in Czech), Ph.D. Thesis. VŠCHT Praha, (August 2004).

[van Paasen 2002] Van Paasen, S.V.B et al. Guideline for Sampling and Analysis of Tar and Particles in Biomass Producer Gases. Final report documenting the guideline, R&D work and dissemination 2002, ECN-C-02-090

[Weber 2001] Weber, R., Sakurai, T. Formation characteristics of PCDD and PCDF during pyrolysis processes, Chemosphere, Volume 45, Issue 8, December 2001, Pages 1111-1117, ISSN 0045-6535

[Xiao, 2009] Xiao, G., et al. Gasification characteristics of MSW and an ANN prediction model, Waste Management, Volume 29, Issue 1, January 2009, Pages 240-244, ISSN 0956-053X

CONTACTS:

Ing. Marek Balas, Ph.D.
Brno University of Technology
Faculty of Mechanical Engineering
Energy Institute
Technicka 2, 616 69 Brno, Czech Republic
Tel.: +420 514142583
e-mail: marek.balas@vutbr.cz