GASIFICATION OF LIVESTOCK WASTE WITH ULTRASUPERHEATED MIXTURE OF STEAM AND CARBON DIOXIDE

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Abstract: Experimental studies of steam and CO_2-assited allothermal gasification of the original (moisture $\alpha = 70\%$) and partly dried pig manure (PM) with $\alpha = 45\%$ and 15% are conducted on a laboratory-scale flow-through gasifier. The high-temperature ($\sim$ 2000 °C) gasification agent is generated by a pulsed-detonation gun (PDG) operating on the stoichiometric natural gas – oxygen mixture. The contents of C, O, and H in the dry feedstock are 45.7, 37.7, and 5.8 %(wt.), respectively. The mass fraction of elements with an atomic mass above 11 a.u. in the feedstock is 6.8 %(wt.). The mineral components in the feedstock are mainly represented by compounds of Si, Ca, P, Mg, K, S, Na, Cl, Al, and Fe. The high heating values of the feedstock at $\alpha = 70\%$ and 0% are 5.8 and 16.8 MJ/kg. The dry off-gas obtained from the original feedstock typically contains 33–41 %(vol.) CO_2, 34–40 %(vol.) CO, 17–22 %(vol.) H_2, 2.5–4.0 %(vol.) CH_4, and 0–2.5 %(vol.) C_xH_y with propane being the highest registered hydrocarbon in C_xH_y (less than 0.1%), i. e., there is no tar as a gasification by-product. The reduction of feedstock moisture allows for increasing the yields of CO, H_2, and CH_4 to 45%, 25%, and 5%, respectively, and reducing the yield of CO_2 to 25%. i. e., the resulting dry off-gas can contain up to 75% combustible gas. The mass of fly ash residue is 10%–17% of the dry mass of the original feedstock. With a decrease in the feedstock moisture to $\alpha = 15\%$, the mass of fly ash increases to 20%–30%, i. e., partly dried feedstock is more easily carried away from the flow-through gasifier. Fly ash is found to contain C, O, P, N, K, and H with trace amounts of Si, Ca, Mg, S, Na, Cl, Al, and Fe. The size of fly ash particles ranges from 0.1 to 35 μm. Results of experiments in terms of the off-gas temperature and composition agree satisfactorily with the results of thermodynamic calculations, if one takes heat losses into account. In the existing version of the laboratory-scale setup, only about 33% of the thermal energy of the high-temperature gasification agent is utilized for feedstock gasification, while the rest 67% are transferred to the coolant and environment. At these conditions, gasification of 1 kg of dry feedstock with the use of 1 kg of stoichiometric methane–oxygen mixture results in the production of 1.91 kg of combustible off-gas (diluted with 25–30 %(vol.) CO_2) and 0.09 kg fly ash. To improve the energy efficiency of the gasification process, it is recommended to apply proper thermal insulation and heat recovery. To increase the yield of combustible gas, it is recommended to use the continuous supply of feedstock from a feeder and to improve mixing of feedstock with the gasifying agent. To increase the carbon conversion efficiency, special measures must be taken to prevent premature entrainment of feedstock particles.

Keywords: pig manure; gasification; steam; carbon dioxide; pulsed detonation gun; generator gas; fly ash

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Figure Captions

Figure 1 Photographs of the PM: (*a*) original feedstock; and (*b*) and (*c*) feedstock dried on a hot surface

Figure 2 Infrared spectra of cellulose (*a*) and of two samples of the original PM: No. 1 (*b*) and No. 2 (*c*)

Figure 3 Mass fractions of elements in PM

Figure 4 Schematic of the experimental setup: *1* — mixing and ignition device; *2* — spark plugs; *3* — PDG; *4* — cooling system; *5* — reactor-gasifier; *6* — gas sampling system; *7* — ionization probes; *8* — oxygen and fuel line valves; *9* — reducers; *10* — pressure sensors; *11* — oxygen receiver; *12* — methane (natural gas) receiver; *13* — oxygen source; and *14* — methane (natural gas) source

Figure 5 Reactor-gasifier with hatches at the top and bottom (*a*) and a splitter pipe for the tangential connection of the PDG (*b*)

Figure 6 Example of gas and wall temperature records in the upper part of a reactor with two stages of wet feedstock gasification: τ_1 — moisture evaporation stage; and τ_2 — gasification stage. Time zero corresponds to the activation of PDG

Figure 7 Example of records of the flow-through gas analyzer (left scale) and gas and wall temperatures in the upper part of the reactor (right scale) in an experiment with loading a portion of 1 kg wet PM into the reactor

Figure 8 Photograph of the fly ash extracted from a "dry" cyclone

Figure 9 Model of the PM gasification process

Figure 10 Compositions of the dry off-gas produced from the original PM with a moisture of 70% at various gasification conditions; the numbers above the columns are the numbers of the experiments in Table 11

Figure 11 Measured dependencies of CO, H_2, CH_4, and C_xH_y volume fractions on the volume fraction of CO_2 in the dry off-gas produced by gasification of wet PM ($\alpha = 70\%$) and wet coffee grounds ($\alpha = 80\%$) (*a*) and dried PM ($\alpha = 15\%$) and sawdust ($\alpha = 15\%$) (*b*)

Figure 12 Measured dependencies of CO, H_2, CH_4, and C_xH_y volume fractions on the volume fraction of CO_2 in the dry off-gas produced by gasification of PM of different moisture (70% to 15%, see Table 11) under different conditions of feedstock loading: batch loading (*1*) and continuous feed (*2*) into the reactor

Figure 13 Mass fractions of elements in dried PM (*1*), fly ash extracted from the "dry" cyclone (*2*), and fly ash extracted from the "wet" cyclone (after drying, *3*)

Figure 14 Oxidative stability of fly ash measured by synchronous thermal analysis: (*a*) sample 1; and (*b*) sample 2

Figure 15 Particle size distribution in fly ash: *1* — experiments No. 3 + No. 6 in Table 11; *2* — experiment No. 3; *3* — experiment No. 6; *4* — experiment No. 7; *5* — experiment No. 9; and *6* — experiment No. 10

Figure 16 Total ion current chromatograms of diethyl ether (*a*) and hexane (*b*) extracts of trimethylsilyl derivatives of condensed products of PM gasification

Table Captions

Table 1 Results of elemental CHNS analysis of the original PM

Table 2 Results of calorimetric measurements of the higher heating value of the original PM

Table 3 Dependence of the mass of the PM sample on the drying time at room temperature

Table 4 Results of calorimetric measurements of the higher heating value of dried PM

Table 5 Elemental composition of dry coffee grounds [47]

Table 6 Elemental composition of wood sawdust [48]

Table 7 Measured composition of detonation products of a stoichiometric methane–oxygen mixture expanded to an initial pressure of 0.1 MPa and a temperature of 2000 K [51]

Table 8 Average statistical composition of PM [52]

Table 9 Model composition of the PM

Table 10 Calculated compositions of the off-gas produced by PM gasification at process temperatures of 1000, 1200, 1500, and 2000 K at a pressure of 0.1 MPa

Table 11 Summary table for conducted experiments

Table 12 Mass balances of PM drying and gasification processes

Table 13 Compositions of the dry off-gas produced by gasification of PM measured in several experiments with a flow gas analyzer and gas chromatographs (marked with an asterisk)

Table 14 Elemental composition of fly ash (%(wt.))

Table 15 Comparison of calculated (equilibrium) and measured compositions of the dry off-gas produced by gasification of PM at a process temperature of 1000 K and pressure of 0.1 MPa

References

1. Merzlaya, G. E., I. V. Shchegoleva, and M. V. Leonov. 2012. Ispol'zovznie svinogo navoza dlya udobreniya sel'skokhozyaystvennykh kul'tur [Use of pig manure for fertilizing agricultural crops]. *Perspektivnoe svinovodstvo: teoriya i praktika* [Prospective pig breeding: Theory and practice] 6:3–9.
2. Kapustin, V. P., and A. V. Uymenov. 2007. Pererabotka otkhodov zhivotnovodstva i ptitsevodstva [Processing of livestock and poultry farming waste]. *Voprosy sovremennoy nauki i praktiki. Universitet im. V. I. Vernadskogo* [Issues of modern science and practice. Vernadsky University] 4(10-2):23–26.
3. Bernal, M. P., J. A. Alburquerque, and R. Moral. 2009. Composting of animal manures and chemical criteria for compost maturity assessment. A review. *Bioresourse Technol.* 100(22):5444–5453.
4. Shalavina, E. V., A. Yu. Bryukhanov, E. V. Vasiliev, R. A. Uvarov, and A. M. Valge. 2020. Biofermentatsiya organitcheskikh otkhodov svinovodcheskogo kompleksa v ustanovke barabannogo tipa [Biofermentation of or-

ganic waste from a pig-breeding complex in a drum-type installation]. *Agrarnaya nauka* [Agricultural Science] 339(6):51–56.

5. Shubin, A. S., and N. V. Syrchina. 2017. Pererabotka svezhego svinogo navoza v orgomineral'nye udobreniya [Processing of fresh pig manure into organomineral fertilizers]. *Voprosy nauki* [Questions of Science] 1:22–26.
6. Li, S., D. Zou, L. Li, L. Wu, F. Liu, X. Zeng, H. Wang, Y. Zhu, and Z. Xiao. 2020. Evolution of heavy metals during thermal treatment of manure: A critical review and outlooks. *Chemosphere* 247:125962.
7. Liang, Y. 2022. A critical review of challenges faced by converting food waste to bioenergy through anaerobic digestion and hydrothermal liquefaction. *Waste Biomass Valori.* 13:781–796.
8. Gaifullin, I. Kh., B. G. Ziganshin, A. V. Shornikov, B. L. Ivanov, and A. N. Zinnatullina. 2024. Teoreticheskie aspekty protsessa polucheniya biogaza pri anaerobnoy fermentatsii organicheskikh otkhodov [Theoretical aspects of the process of biogas production during anaerobic fermentation of organic waste]. *Tekhnika i tekhnologii v zhivotnovodstve* [Engineering and Technology in Animal Husbandry] 14(1):90–95. doi: 10.22314/27132064-2024-1-90.
9. Møller, H. B., H. S. Jensen, L. Tobiasen, and M. N. Hansen. 2007. Heavy metal and phosphorus content of fractions from manure treatment and incineration. *Environ. Technol.* 28(12):1403–1418. doi: 10.1080/09593332808618900.
10. Gebreegziabher, T., A. Oyedun, Z. Yu, W . Maojian, Z. Yi, L. Jin, and C. Hui. 2014. Biomass drying for an integrated power plant: Efective utilization of waste heat. *Comput.-Aided Chem. En.* 33:1555–1560.
11. Babaei, K., A. Bozorg, and A. Tavasoli. 2021. Hydrogen-rich gas production through supercritical water gasification of chicken manure over activated carbon/ceria-based nickel catalysts. *J. Anal. Appl. Pyrol.* 159:105318.
12. Du, M., S. Liu, J. Sun, H. Jin, Y. Chen, and L. Guo. 2023. Clean conversion of pig manure via supercritical water gasification: Hydrogen-enriched syngas generation, mechanisms analysis, and environmental impacts. *J. Clean. Prod.* 420:138455. doi: 10.1016/j.jclepro.2023.138455.
13. Kumar, A., D. Jones, and M. Hanna. 2009. Thermochemical biomass gasification: A review of the current status of the technology. *Energies* 2:556–581.
14. Ro, K., J. Libra, S. Bae, N. Berge, J. Flora, and R. Pecenka. 2019. Combustion behavior of animal-manure-based hydrochar and pyrochar. *ACS Sustain. Chem. Eng.* 7:470–478.
15. Szulc, W., B. Rutkowska, S. Gawroński, and E. Wszelaczyńska. 2021. Possibilities of using organic waste after biological and physical processing — an overview. *Processes* 9(9):1501.
16. Islam, M. N., and J. H. Park. 2018. A short review on hydrothermal liquefaction of livestock manure and a chance for Korea to advance swine manure to bio-oil technology. *J. Mater. Cycles Waste* 20(1):1–9.
17. Zhou, S., H. Liang, L. Han, G. Huang, and Z. Yang. 2019. The influence of manure feedstock, slow pyrolysis, and hydrothermal temperature on manure thermochemical and combustion properties. *Waste Manage.* 88: 85–95.
18. Spiridonova A. V., V. P. Druzyanova, O. M. Osmonov, O. K. Tarabukina, and Zh. G. Sivtseva. 2022. Piroliznaya tekhnologiya — perspektivnyy sposob utilizatsii tverdogo vysushennogo navoza [Pyrolysis technology is a promising method for utilizing solid dried manure]. *Dal'nevostochnyy agrarnyy vestnik* [Far Eastern Agrarian Bulletin] 1(61):143–150. doi: 10.24412/1999-6837-2022-1-143-150.
19. Su, G., H. C. Ong, N. W. Mohd Zulkifli, *et al.* 2022. Valorization of animal manure via pyrolysis for bioenergy: A review. *J. Clean Prod.* 343(2):130965. doi: 10.1016/j.jclepro.2022.130965.
20. McKendry, P. 2002. Energy production from biomass (part 3): Gasification technologies. *Bioresourse Technol.* 83(1):55–63.
21. Zhang, S., Huang, F., Morishita, K., and T. Takarada. 2009. Hydrogen production from manure by low temperature gasification. *Asia-Pac. Power Energ.* doi: 10.1109/appeec.2009.4918410.
22. Basu, P. 2010. *Biomass gasifcation and pyrolysis: Practical design and theory*. New York, NY: Academic Press. 375 p.
23. Lombardi, L., E. Carnevale, and A. Corti. 2015. A review of technologies and performances of thermal treatment systems for energy recovery from waste. *Waste Manage.* 37:26–44.
24. Vamvuka, D., S. Sfakiotakis, and O. Pantelaki. 2019. Evaluation of gaseous and solid products from the pyrolysis of waste biomass blends for energetic and environmental applications. *Fuel* 236:574–582.
25. Sharara, M. A., and S. S. Sadaka. 2018. Opportunities and barriers to bioenergy conversion techniques and their potential implementation on swine manure. *Energies* 11:957.
26. Zhang, X., X. Mao, L. Pi, T. Wu, and Y. Hu. 2019. Adsorptive and capacitive properties of the activated carbons derived from pig manure residues. *J. Environmental Chemical Engineering* 7:103066.
27. Park, M. H., S. Kumar, and C. Ra. 2012. Solid waste from swine wastewater as a fuel source for heat production. *Asian Austral. J. Anim.* 25:1627–1633.
28. Wu, H., M. A. Hanna, and D. D. Jones. 2013. Life cycle assessment of greenhouse gas emissions of feedlot manure management practices: Land application versus gasification. *Biomass Bioenerg.* 54:260–266.
29. Mohan, D., C. U. Pittman, and P. H. Steele. 2006. Pyrolysis of wood/biomass for bio-oil: A critical review. *Energ. Fuel.* 20:848–889.
30. He, B. J., Y. Zhang, Y. Yin, T. L. Funk, and G. Riskowski. 2001. Preliminary characterization of raw oil products

from the thermochemical conversion of swine manure. *T. ASAE* 44:1865–1871.

31. Mullen, C. A., and A. A. Boateng. 2008. Chemical composition of bio-oils produced by fast pyrolysis of two energy crops. *Energ. Fuel.* 22:2104–2109.
32. Azuara, M., S. R. Kersten, and A. M. J. Kootstra. 2013. Recycling phosphorus by fast pyrolysis of pig manure: Concentration and extraction of phosphorus combined with the formation of value-added pyrolysis products. *Biomass Bioenerg.* 49:171–180.
33. Cao, J., X. Xiao, S. Zhang, X. Zhao, K. Sato, Y. Ogawa, X. Y. Wei, and T. Takarada. 2011. Preparation and characterization of bio-oils from internally circulating fluidized-bed pyrolyses of municipal, livestock, and wood waste. *Bioresourse Technol.* 102:2009–2015.
34. Elliott, D. C. 2007. Historical developments in hydroprocessing bio-oils. *Energ. Fuel.* 21:1792–1815.
35. Cantrell, K. B., P. G. Hunt, M. Uchimiya, J. M. Novak, and K. S. Ro. 2012. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. *Bioresourse Technol.* 107:419–428.
36. Takanabe, K., K. Aika, K. Seshan, and L. Lefferts. 2004. Sustainable hydrogen from bio-oil–steam reforming of acetic acid as a model oxygenate. *J. Catal.* 227:101–108.
37. Burra, K. G., M. S. Hussein, R. S. Amano, and A. K. Gupta. 2016. Syngas evolutionary behavior during chicken manure pyrolysis and air gasification. *Appl. Energ.* 181(1):408–415.
38. Lombardi, L., E. Carnevale, and A. Corti. 2015. A review of technologies and performances of thermal treatment systems for energy recovery from waste. *Waste Manage.* 37:26–44.
39. Maric, J., T. Berdugo Vilches, S. Pissot, I. Cañete Vela, M. Gyllenhammar, and M. Seemann. 2020. Emissions of dioxins and furans during steam gasification of automotive shredder residue; experiences from the Chalmers 2–4-MW indirect gasifier. *Waste Manage.* 102:114–121. doi: 10.1016/j.wasman.2019.10.037.
40. Messerle, V. E., A. B. Ustimenko, O. A. Lavrichshev, and M. K. Nugman. 2024. The gasification and pyrolysis of biomass using a plasma system. *Energies* 17:5594. doi: 10.3390/en17225594.
41. Rosyadi, I., S. Suyitno, A. X. Ilyas, A. Faishal, A. Budiono, and M. Yusuf. 2022. Producing hydrogen-rich syngas via microwave heating and co-gasification: A systematic review. *Biofuel Research J.* 33:1573–1591. doi: 10.18331/BRJ2022.9.1.4.
42. Frolov, S. M., V. A. Smetanyuk, K. A. Avdeev, and S. A. Nabatnikov. 24.04.2019. Sposob polucheniya sil'no peregretogo para i ustroystvo detonatsionnogo parogeneratora (varianty) [Method for obtaining highly overheated steam and detonation steam generator device (options)]. Patent of Russian Federation No. 2686138. Priority date 26.02.2018.
43. Frolov, S. M., A. S. Silantiev, I. A. Sadykov, *et al.* 2023. Composition and textural characteristics of char powders produced by thermomechanical processing of sunflower seed husks. *Powders* 2:624–638. doi: 10.3390/powders2030039.
44. Frolov, S. M., A. S. Silantiev, I. A. Sadykov, V. A. Smetanyuk, F. S. Frolov, J. K. Hasiak, A. B. Vorob'ev, A. V. Inozemtsev, and J. O. Inozemtsev. 2023. Gasification of waste machine oil by the ultra-superheated mixture of steam and carbon dioxide. *Waste* 1:515–531. doi: 10.3390/waste1020031.
45. Frolov, S. M. 2023. Organic waste gasification by ultra-superheated steam. *Energies* 16:219. doi: 10.3390/en16010219.
46. Frolov, S. M., V. A. Smetanyuk, I. A. Sadykov, A. S. Silantiev, F. S. Frolov, V. Y. Popkova, J. K. Hasiak, A. G. Buyanovskaya, R. U. Takazova, T. V. Dudareva, V. G. Bekeshev, A. B. Vorobyov, A. V. Inozemtsev, and J. O. Inozemtsev. 2025. High-temperature steam- and CO_2-assisted gasification of oil sludge and petcoke. *Clean Technologies* 7:17. doi: 10.3390/cleantechnol7010017.
47. Gubin, A. V., K. B. Larionov, R. D. Gerasimov, and A. Ya. Pak. 2022. Poluchenie polukoksa iz kofeynogo zhmykha v katchestve syr'ya dlya sinteza karbida kremniya [Obtaining semi-coke from coffee cake as a raw material for the synthesis of silicon carbide]. *Mezhdunarodnyy zh. prikladnykh i fundamental'nykh issledovaniy* [Int. J. Applied Fundamental Research] 12:75–81. Available at: https://applied-research.ru/ru/article/view?id=13487 (accessed April 21, 2025).
48. Zaichenko, V. M., V. A. Lavrenov, and Yu. M. Faleeva. 2023. Study of the slow pyrolysis of lignin, hemicellulose, and cellulose and the effect of their interaction in plant biomass. *SOLID FUEL CHEM.* 57(6):428–436. doi: 10.3103/s0361521923060083. EDN: YEWJNN.
49. SDToolBox — Numerical tools for shock and detonation wave modeling. Available at: https://shepherd.caltech.edu/EDL/publications/reprints/ShockDetonation.pdf (accessed April 21, 2025).
50. Goodwin, D. G., H. K. Moffat, I. Schoegl, R. L. Speth, and B. W. Weber. 2023. Cantera: An object-oriented software toolkit for chemical kinetics, thermodynamics, and transport processes. Version 3.0.0. doi: 10.5281/zenodo.8137090.
51. Frolov, S. M., V. A. Smetanyuk, I. A. Sadykov, A. S. Silantiev, V. S. Aksenov, I. O. Shamshin, K. A. Avdeev, and F. S. Frolov. 2022. Avtotermicheskaya konversiya prirodnogo gaza i allotermicheskaya gazifikatsiya zhidkikh i tverdykh organicheskikh otkhodov ul'traperegretym vodyanym parom [Autothermal natural gas conversion and allothermal gasification of liquid and solid organic wastes by ultrasuperheated steam]. *Goren. Vzryv (Mosk.) — Combustion and Explosion* 15(2):75–87.
52. Eskov, A. I., M. N. Novikov, and S. M. Lukin. 2001. *Spravochnaya kniga po proizvodstvu i primeneniyu organicheskikh udobreniy* [Reference book on the production and

use of organic fertilizers]. Moscow: Publishing House of the Russian Academy of Agricultural Sciences. 495 p.

53. Shigabaeva, G. N. 2014. Elementnyy sostav i soderzhanie funktsional'nykh grupp guminovykh veshchestv pochv i torfov razlichnogo proiskhozhdeniya [Elemental composition and content of functional groups of humic substances of soils and peats of different origin]. *Vestnik Tyumenskogo gosudarstvennogo universiteta* [Bulletin of Tyumen State University. Ecology] 12:45–53.

54. Avdeev, K. A., A. S. Silantiev, V. A. Smetanyuk, V. G. Piletsky, F. S. Frolov, and S. M. Frolov. 2024. Usloviya samozapitki impul'sno-detonatsionnykh pushek energeticheskim gazom pri gazifikatsii burykh ugley produktami detonatsii [Conditions for self-feeding of pulsed detonation guns with energy gas during gasification of brown coals by detonation products]. *Goren. Vzryv (Mosk.) — Combustion and Explosion* 17(1):95–104. doi: 10.30826/CE24170108.

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