GASIFICATION OF ORGANIC WASTE WITH ULTRASUPERHEATED STEAM AND CARBON DIOXIDE

S. M. Frolov

N. N. Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences, 4 Kosygin Str., Moscow 119991, Russian Federation

Abstract: A literature review on allothermal gasification of organic waste in steam and carbon dioxide environment at atmospheric pressure is presented. Two groups of technologies are considered, namely, low-temperature (500–1000 °C) and high-temperature (above 1200 °C). The existing low-temperature gasification technologies are shown to provide the syngas of relatively low quality, exhibit low efficiency and complex control of gas composition, and low yields of syngas. The main efforts to improve such technologies are directed at preprocessing of feedstocks and additional processing of the product syngas as well as increasing the reactivity of the feedstocks with the help of catalysts. Unlike low-temperature gasification, high-temperature plasma gasification provides high quality syngas, exhibits high process efficiency and easy control of gas composition, and high yields of syngas. However, arc and microwave plasma technologies require huge energy consumption as well as special construction materials and refractory lining for gasifier walls. Moreover, gasification of feedstocks in plasma reactors mainly occurs at temperatures of 1200–2000 °C, so that the gas–plasma transition turns out to be an unclaimed but highly energy-intense intermediate stage. An environmentally friendly detonation gun technology for organic waste gasification is proposed and demonstrated as a more effective alternative.

Keywords: organic waste; allothermal gasification; steam; carbon dioxide; detonation gun; ultrasuperheated steam

DOI: 10.30826/CE21140308

Figure Captions

Figure 1 Equilibrium composition of detonation products of stoichiometric ternary mixtures of fuel gas – O_2 – steam; circles *1* correspond to the temperature and composition at the Chapman–Jouguet point and circles *2* correspond to the temperature and composition of the detonation products isentropically expanded to 0.1 MPa. Fuel gas: (*a*) syngas with $H_2/CO = 1$; (*b*) syngas with $H_2/CO = 2$; (*c*) CH_4; and (*d*) C_3H_8

Figure 2 Schematics of pulsed (*a*) and continuous (*b*) detonation guns [35]

Figure 3 Three-dimensional model and photographs of a detonation gun 50 mm in diameter

Figure 4 Temperature and composition of detonation products of stoichiometric ternary mixtures of C_3H_8 (*a*) and CH_4 (*b*) with oxygen and steam depending on steam volume fraction X after isentropic expansion to 0.1 MPa. The shaded areas indicate the conditions under which detonation is detected experimentally

Figure 5 Schematic of a plant for high-temperature steam gasification of organic waste

Figure 6 Schematic of a plant for high-temperature steam gasification of organic waste with a branched detonation gun [38]

Figure 7 Schematic, computational mesh, and boundary conditions for calculating a flow pattern in a vortex reactor [82]

Figure 8 (*a*) Calculated fields of gas temperature and velocity vector in a vortex reactor at three instants of time during one shot of the detonation gun [82]

Figure 9 Instantaneous distribution functions of steam temperature at particle positions (top) and the predicted dependences of characteristic instantaneous steam temperatures in the reactor: maximum, mass-averaged, minimum, and at particle positions [82]

Figure 10 Predicted distribution function of particle residence time in a vortex reactor [82]

Figure 11 A pilot plant for steam gasification of organic waste with a capacity of up to 100 kg/h with a spherical reactor and a branched detonation gun (*a*); and thermal glow of a detonation gun during operation (*b*)

Table Captions

Table 1 Experimental studies on low-temperature steam gasification of carbon containing material (CCM) at 0.1 MPa

Table 2 Experimental studies on low-temperature gasification of CCM by steam and/or carbon dioxide at 0.1 MPa

Table 3 Experimental studies of high-temperature gasification of CCM by steam and/or CO_2 at 0.1 MPa

References

1. Higman, C., and M. Van der Burgt. 2005. *Gasification*. 1st ed. Gulf Professional Publishing. 391 p.
2. Rezaiyan, J., and N. Cheremisinoff. 2005. *Gasification technologies. A primer for engineers and scientists*. 1st ed. Boca Raton, FL: CRC Press, Taylor & Francis Group. 360 p.
3. Basu, P. 2010. *Biomass gasification and pyrolysis: Practical design and theory*. Burlington, MA: Academic Press. 376 p.
4. Bain, R. L., and K. Broer. 2011. Gasification. *Thermochemical processing of biomass: Conversion into fuels, chemicals and power*. Ed. R. C. Brown. 1st ed. John Wiley & Sons. 47–77.
5. Chen, W.-H., J. Peng, and X. T. Bi. 2015. A state-of-the-art review of biomass torrefaction, densification and applications. *Renew. Sust. Energ. Rev.* 44:847–866.
6. Quaak, P., H. Knoef, and H. Stassen. 1999. Energy from biomass: A review of combustion and gasification technologies. *World Bank Technical Papers*. Washington, D.C.: World Bank. Paper 422. doi: 10.1596/0-8213-4335-1.
7. Santoleri, J. J., J. Reynolds, and L. Theodore. 2000. *Introduction to hazardous waste incineration*. 2nd ed. New York, NY: Wiley. 656 p.
8. Ahrenfeldt, J., T. P. Thomsen, U. Henriksen, and L. R. Clausen. 2013. Biomass gasification cogeneration — a review of state-of-the-art technology and near future perspectives. *Appl. Therm. Eng.* 50:1407–1417.
9. Ismail, T. M., and M. A. El-Salam. 2017. Parametric studies on biomass gasification process on updraft gasifier high temperature air gasification. *Appl. Therm. Eng.* 112:1460–1473.
10. Karl, J., and T. Proll. 2018. Steam gasification of biomass in dual fluidized bed gasifiers: A review. *Renew. Sust. Energ. Rev.* 98:64–78.
11. Abanades, S., S. Rodat, and H. Boujjat. 2021. Solar thermochemical green fuels production: A review of biomass pyro-gasification, solar reactor concepts and modelling methods. *Energies* 14:1494.
12. Bartocci, P., M. Zampilli, G. Bidini, and F. Fantozzi. 2018. Hydrogen-rich gas production through steam gasification of charcoal pellet. *Appl. Therm. Eng.* 132:817–823.
13. Wu, H., Q. Liu, Z. Bai, G. Xie, J. Zheng, and B. Su. Thermodynamics analysis of a novel steam/air biomass gasification combined cooling, heating and power system with solar energy. *Appl. Therm. Eng.* 164:114494.
14. Jayaraman, K., I. Goekalp, and S. Jeyakumar. 2017. Estimation of synergetic effects of CO_2 in high ash coal-char steam gasification. *Appl. Therm. Eng.* 110:991–998.
15. Zheng, X., Z. Ying, B. Wang, and C. Chen. 2018. Hydrogen and syngas production from municipal solid waste (MSW) gasification via reusing CO_2. *Appl. Therm. Eng.* 144:242–247.
16. Darivakis, G. S., J. B. Howard, and W. A. Peters. 1990. Release rates of condensables and total volatiles from rapid devolatilization of polyethylene and polystyrene. *Combust. Sci. Technol.* 74:267–281.
17. Ki-Bum, P., J. Yong-Seong, G. Begum, and K. JooSik. 2019. Characteristics of a new type continuous two-stage pyrolysis of waste polyethylene. *Energy* 166:343–351.
18. Chen, Z., X. Zhang, L. Gao, and S. Li. 2017. Thermal analysis of supercritical water gasification of coal for power generation with partial heat recovery. *Appl. Therm. Eng.* 111:1287–1295.
19. Jared, P., J. Ciferno, and J. Marano. June 2020. Benchmarking biomass gasification technologies for fuels, chemicals and hydrogen production. U.S. Department of Energy, National Energy Technology Laboratory. 65 p.
20. Rauch, R., J. Hrbek, and H. Hofbauer. 2014. Biomass gasification for synthesis gas production and applications of syngas. *WIRES Energy Environ.* 3:343– 362.
21. Ma, W., T. Wenga, F. J. Frandsen, B. Yan, and G. Chen. 2020. The fate of chlorine during MSW incineration: Vaporization, transformation, deposition, corrosion and remedies. *Prog. Energ. Combust.* 76:100789.
22. Holladay, J. D., J. Hu, D. L. King, and Y. Wang. 2009. An overview of hydrogen production technologies. *Catal. Today* 139:244–260.
23. Ruj, B., and S. Ghosh. 2014. Technological aspects for thermal plasma treatment of municipal solid waste — a review. *Fuel Process. Technol.* 126:298–308.
24. Mazzoni, L., I. Janajreh, S. Elagroudy, and C. Ghenai. 2020. Modeling of plasma and entrained flow co-gasification of MSW and petroleum sludge. *Energy* 196:117001.
25. Lahijani, P., Z. A. Zainal, A. R. Mohamed, and M. Mohammadi. 2014. Microwave-enhanced CO_2 gasification of oil palm shell char. *Bioresource Technol.* 158:193–200.
26. He, L., Y. Ma, C. Yue, *et al.* 2021. Transformation mechanisms of organic S/N/O compounds during microwave pyrolysis of oil shale: A comparative research with conventional pyrolysis. *Fuel Process. Technol.* 212:106605.
27. Arena, U. 2012. Process and technological aspects of municipal solid waste gasification: A review. *Waste Manage.* 32:625–639.
28. Westinghouse, W. P. C. 2013. Plasma gasification is the next generation of energy from waste technology. *USEA Annual Meeting*. Washington, D.C. 1–16.

29. Wnukowski, M. 2014. Decomposition of tars in microwave plasma — preliminary results. *Ecol. Eng.* 15:23–28.

30. Cothran, C. 2015. Identifying likely late-stage UK WTE projects. *Syngas Technologies Conference*. Colorado Springs, CO: Global Syngas Technologies Council. 13 p.

31. Messenger, B. 2016. Air products to ditch plasma gasification waste to energy plants in Teesside. Waste Management World.

32. Simkins, G., and L. Walsh. 2016. Reasons for TV1 failure revealed. Twickenham. ENDS Report.

33. Bebelin, I. N., A. G. Volkov, A. N. Gryaznov, and S. P. Malyshenko. 1997. Development and investigation of an experimental hydrogen–oxygen steam generator of 10-MW thermal capacity. *Therm. Eng.* 44(8):657–662.

34. Sariev, V. N., V. A. Veretennikov, and V. V. Troyachenko. Sistema kompleksnoy bezotkhodnoy pererabotki tverdykh bytovykh i promyshlennykh otkhodov [System of complex recycling of solid domestic and industrial waste]. Patent of Russian Federation No. 2648737 dated 28.03.2018. Priority dated 12.08.2016.

35. Frolov, S. M., V. A. Smetanyuk, K. A. Avdeev, and S. A. Nabatnikov. 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 dated 24.04.2019. Priority dated 26.02.2018.

36. Saxena, S. C., and C. K. Jotshi. 1996. Management and combustion of hazardous wastes. *Prog. Energ. Combust.* 22(5):401–425.

37. Frolov, S. M., V. A. Smetanyuk, and S. A. Nabatnikov. Sposob gazifikatsii uglya v sil'no peregretom vodyanom pare i ustroystvo dlya ego osushchestvleniya [Method of gasification of coal in a highly overheated water vapor and device for its implementation]. Patent of Russian Federation No. 2683751 dated 01.04.2019. Priority dated 24.05.2018 (WO2019/226074 A1 dated 28.11.2019).

38. Frolov, S. M., S. A. Nabatnikov, K. V. Diesperov, and E. R. Achildiev. Sposob obezzarazhivaniya letuchey zoly, obrazuyushcheysya pri szhiganii otkhodov, i ustroystvo dlya ego osushchestvleniya [Method for decontamination of a fly ash formed during burning of wastes and a device for its implementation]. Patent of Russian Federation No. 2739241 dated 22.12.2020, priority dated 11.06.2020.

39. Roy, G. D., S. M. Frolov, A. A. Borisov, and D. W. Netzer. 2004. Pulse detonation propulsion: Challenges, current status, and future perspective. *Prog. Energ. Combust.* 30(6):545–672.

40. Bykovskii, F. A., and S. A. Zhdan. 2013. *Nepreryvnaya spinovaya detonatsiya* [Continuous spinning detonation]. Novosibirsk: Lavrentiev Institute of Hydrodynamics Publs. 422 p.

41. Rauch, R., J. Hrbek, and H. Hofbauer. 2013. Biomass gasification for synthesis gas production and applications of the syngas. *WIRES Energy Environ.* doi: 10.1002/wene.97.

42. Mahinpey, N., and A. Gomez. 2016. Review of gasification fundamentals and new findings: Reactors, feedstock, and kinetic studies. *Chem. Eng. Sci.* 148:14–31.

43. Awasthi, A. K., *et al.* 2017. Plastic solid waste utilization technologies: A review. *IOP Conf. Ser. — Mat. Sci.* 263:022024.

44. Zhang, Y., P. Xu, S. Liang, B. Liu, Y. Shuai, and B. Li. 2019. Exergy analysis of hydrogen production from steam gasification of biomass: A review. *Int. J. Hydrogen Energ.* 44(28):14290–14302.

45. Inayat, A., M. Raza, Z. Khan, C. Ghenai, M. Aslam, and M. S. M. Ayoub. 2020. Flowsheet modeling and simulation of biomass steam gasification for hydrogen production. *Chem. Eng. Technol.* 43(4):649–660.

46. Indrawan, N., A. Kumar, M. Moliere, K. A. Sallam, and R. L. Huhnke. 2020. Distributed power generation via gasification of biomass and municipal solid waste: A review. *J. Energy Inst.* 93:2293–2313.

47. Zhan, L., L. Jiang, Y. Zhang, B. Gao, and Z. Xu. 2020. Reduction, detoxification and recycling of solid waste by hydrothermal technology: A review. *Chem. Eng. J.* 390:124651.

48. Siwal,S. S., Q. Zhang, C. Sun, S. Thakur, V. K. Gupta, and V. K. Thakur. 2020. Energy production from steam gasification processes and parameters that contemplate in biomass gasifier — A review. *Bioresource Technol.* 297:122481.

49. Galvagno, S., S. Casu, G. Casciaro, M. Martino, A. Russo, and S. Portofino. 2006. Steam gasification of Refuse-Derived Fuel (RDF): Influence of process temperature on yield and product composition. *Energ. Fuel* 20:2284–2288.

50. Galvagno, S., G. Casciaro, S. Casu, M. Martino, C. Mingazzini, A. Russo, and S. Portofino. 2009. Steam gasification of tire waste, poplar, and refuse-derived fuel: A comparative analysis. *Waste Manage.* 29:678–689.

51. Umeki, K., K. Yamamoto, T. Namioka, and K. Yoshikawa. 2010. High temperature steam-only gasification of woody biomass. *Appl. Energ.* 87:791–798.

52. Pieratti, E., M. Baratieri, S. Ceschini, L. Tognana, and P. Baggio. 2011. Syngas suitability for solid oxide fuel cells applications produced via biomass steam gasification process: Experimental and modeling analysis. *J. Power Sources* 196(23):10038–10049.

53. Soni, C. G., A. K. Dalai, T. Pugsley, and T. Fonstad. 2011. Steam gasification of meat and bone meal in a two-stage fixed-bed reactor system. *Asia-Pac. J. Chem. Eng.* 6:71–77.

54. Portofino, S., A. Donatelli, P. Iovane, *et al.* 2013. Steam gasification of waste tyre: Influence of process temperature on yield and product composition. *Waste Manage.* 33(3):672–678.

55. Wilk, V., and H. Hofbauer. 2013. Conversion of mixed plastic wastes in a dual fluidized bed steam gasifier. *Fuel* 107:787–799.

56. Pilon, G., and J.-M. Lavoie. 2013. Pyrolysis of switchgrass (Panicum virgatum L.) at low temperatures within N_2 and CO_2 environments: Product yield study. *ACS Sustain. Chem. Eng.* 1:198–204.

57. Guizani, C., F. J. Escudero Sanz, and S. Salvador. 2014. Effects of CO_2 on biomass fast pyrolysis: Reaction rate, gas yields and char reactive properties. *Fuel* 116:310–320.
58. Sadhwani, N., S. Adhikari, and M. R. Eden. 2016. Biomass gasification using carbon dioxide: Effect of temperature, CO_2/C ratio, and the study of reactions influencing the process. *Ind. Eng. Chem. Res.* 55:2883–2891.
59. Eshun, J., L. Wang, E. Ansah, A. Shahbazi, K. Schimmel, V. Kabadi, and S. Aravamudhan. 2017. Characterization of the physicochemical and structural evolution of biomass particles during combined pyrolysis and CO_2 gasification. *J. Energy Inst.* 92(1):82–93. doi: 10.1016/j.joei.2017.11.003.
60. Minkova, V., S. P. Marinov, R. Zanzi, *et al.* 2000. Thermochemical treatment of biomass in a flow of steam or in a mixture of steam and carbon dioxide. *Fuel Process. Technol.* 61(1):45–52.
61. Kraft, S., F. Kirnbauer, and H. Hofbauer. 2017. CPFD simulations of an industrial-sized dual fluidized bed steam gasification system of biomass with 8 MW fuel input. *Powder Technol.* 190:408–420.
62. Eri, Q., J. Peng, and X. Zhao. 2018. CFD simulation of biomass steam gasification in a fluidized bed based on a multi-composition multi-step kinetic model. *Appl. Therm. Eng.* 129:1358–1368.
63. Yan, L., Y. Cao, H. Zhou, and B. He. 2018. Investigation on biomass steam gasification in a dual fluidized bed reactor with the granular kinetic theory. *Bioresource Technol.* 269:384–392.
64. Qi, T., T. Lei, B. Yan, *et al.* 2019. Biomass steam gasification in bubbling fluidized bed for higher–H_2 syngas: CFD simulation with coarse grain model. *Int. J. Hydrogen Energ.* 44:6448–6460.
65. Yang, S., F. Fan, Y. Wei, *et al.* 2020. Three-dimensional MP-PIC simulation of the steam gasification of biomass in a spouted bed gasifier. *Energ. Convers. Manage.* 210:112689.
66. Frolov, S. M. 2016. Vliyanie turbulentnosti na srednyuyu skorost' khimicheskikh prevrashcheniy: obzor [The effect of turbulence on the average rate of chemical transformations: A review]. *Goren. Vzryv (Mosk.) — Combustion and Explosion* 9(1):43–58.
67. Billaud, J., S. Valin, M. Peyrot, and S. Salvador. 2016. Influence of H_2O, CO_2 and O_2 addition on biomass gasification in entrained flow reactor conditions: Experiments and modelling. *Fuel* 166:166–178.
68. Shie, J. L., F. J. Tsou, K. L. Lin, and C. Y. Chang. 2010. Bioenergy and products from thermal pyrolysis of rice straw using plasma torch. *Bioresource Technol.* 101:761–768.
69. Hlina, M., M. Hrabovsky, T. Kavka, and M. Konrad. 2014. Production of high quality syngas from argon/water plasma gasification of biomass and waste. *Waste Manage.* 34:63–66.
70. Agon, N., M. Hrabovsky, O. Chumak, *et al.* 2016. Plasma gasification or refuse derived fuel in a single-stage system using different gasifying agents. *Waste Manage.* 47:246–255.
71. Hrabovsky, M., M. Hlina, V. Kopecky, A. Maslani, O. Zivny, P. Krenek, and O. Hurba. 2017. Steam plasma treatment of organic substances for hydrogen and syngas production. *Plasma Chem. Plasma P.* 37(3):739–762.
72. Wang, M., M. Mao, M. Zhang, *et al.* 2019. Highly efficient treatment of textile dyeing sludge by CO_2 thermal plasma gasification. *Waste Manage.* 90:29–36.
73. Vecten, S., M. Wilkinson, N. Bimbo, R. Dawson, and B. M. J. Herbert. 2021. Hydrogen-rich syngas production from biomass in a steam microwave-induced plasma gasification reactor. *Bioresource Technol.* 337:125324. doi: 10.1016/j.biortech.2021.125324.
74. Piatkowski, N., C. Wieckert, and A. Steinfeld. 2009. Experimental investigation of a packed-bed solar reactor for the steam gasification of carbonaceous feedstocks. *Fuel Process. Technol.* 90:360–366.
75. Frolov, S. M., F. S. Frolov, and V. A. Smetanyuk. 16.10.2014. Detonation forming method and device for the implementation thereof. Patent WO/2016/060582 A1, B21D 26/08 (2006.01), published on 21.04.2016.
76. Frolov, S. M., and F. S. Frolov. 19.02.2013. Device for fuel combustion in a continuous detonation wave. Patent WO 2014/129920 A1, F23R 7/00, published on 28.08.2014.
77. Frolov, S. M., V. A. Smetanyuk, I. O. Shamshin, A. S. Koval', F. S. Frolov, and S. A. Nabatnikov. 2020. Cyclic detonation of the ternary gas mixture propane–oxygen–steam for producing highly superheated steam. *Dokl. Phys. Chem.* 490(2):14–17. doi: 10.1134/S0012501620020025.
78. Frolov, S. M., V. S. Aksenov, K. A. Avdeev, A. A. Borisov, V. S. Ivanov, A. S. Koval', S. N. Medvedev, V. A. Smetanyuk, F. S. Frolov, and I. O. Shamshin. 2013. Teplovye ispytaniya impul'sno-detonatsionnoy gazovoy gorelki bez prinuditel'nogo okhlazhdeniya [Thermal testing of a pulsed detonation burner without forces cooling]. *Goren. Vzryv (Mosk.) — Combustion and Explosion* 6:98–103.
79. Frolov, S. M., V. A. Smetanyuk, I. O. Shamshin, A. S. Koval', F. S. Frolov, and S. A. Nabatnikov. 2019. Poluchenie sil'no peregretogo vodyanogo para s pomoshch'yu tsiklicheskoy detonatsii troynoy gazovoy smesi "propan – kislorod – vodyanoy par" [Generation of highly superheated steam by pulsed detonation of the ternary gas "propane–oxygen–steam" mixture]. *Goren. Vzryv (Mosk.) — Combustion and Explosion* 12(4):95–103.
80. Frolov, S. M., V. A. Smetanyuk, I. O. Shamshin, I. A. Sadykov, A. S. Koval', and F. S. Frolov. 2021. Production of highly superheated steam by cyclic detonations of propane and methane–steam mixtures with oxygen for waste gasification. *Appl. Therm. Eng.* 183(1):116195. doi: 10.1016/j.applthermaleng.2020.116195.
81. Frolov, S. M., V. S. Aksenov, A. V. Dubrovskii, A. E. Zangiev, V. S. Ivanov, S. N. Medvedev, and I. O. Shamshin. 2015. Chemiionization and acoustic diagnostics of the process in continuous- and pulse-detonation combustors. *Dokl. Phys. Chem.* 465(1):273–278.
82. Frolov, S. M., V. A. Smetanyuk, and S. S. Sergeev. 2020. Reactor for waste gasification with highly superheat-

ed steam. *Dokl. Phys. Chem.* 495(2):191–195. doi: 10.1134/S0012501620120039.

83. Morin, C., C. Chauveau, and I. Gökalp. 2000. Droplet vaporisation characteristics of vegetable oil derived biofuels at high temperatures. *Exp. Therm. Fluid Sci.* 21(1-3):41–50. doi: 10.1016/s0894-1777(99)00052-7.

84. Basevich, V. Ya., S. N. Medvedev, S. M. Frolov, F. S. Frolov, B. Basara, and P. Priesching. 2016. Makrokineticheskaya model' dlya rascheta emissii sazhi v dizele [Macrokinetic model for calculation of soot emissions in Diesel engine]. *Goren. Vzryv (Mosk.) — Combustion and Explosion* 9(3):36–46.

Received August 15, 2021

Contributor

Frolov Sergey M. (b. 1959) — Doctor of Science in physics and mathematics, head of department, head of laboratory, N. N. Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences, 4 Kosygin Str., Moscow 119991, Russian Federation; professor, National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 31 Kashirskoe Sh., Moscow 115409, Russian Federation; smfrol@chph.ras.ru