Thermochemical processing of organic waste

N Timerbaev¹, R Safin², I Mazarov¹ and T Stepanova²
¹ Kazan State Power Engineering University, Kazan, Krasnoselskaya Street, 51, 420066, Russian Federation
² Kazan National Research Technological University, Kazan, Karl Marx Street, 68, 420015, Russian Federation

Abstract. The article considers the problems of creation of new types of energy based on the processing of organic waste and methods for their transformation into gaseous, liquid and solid fuels. The technological scheme of complex processing of organic waste into liquid and solid fuels is presented. We consider the unit for organic waste processing with the possibility of generating not only electrical energy, but also a valuable product, namely an adsorbent.

1. Introduction
Currently, the problem of creating new types of fuels based on the processing of organic waste is of immediate interest. The research of complex processing of organic waste into liquid and solid fuels is being conducted at KNRTU [5]. Fig. 1 shows a flowchart of complex processing of organic waste into liquid and solid fuels, in which solid fuels are converted into activated carbon and generator gas of higher quality for supply into the internal combustion engine [1].

![Technological scheme of complex processing of organic waste.](image)

Activated carbon, electrical energy, and bio-oil obtained by condensation of the resulting vapor-gas mixture are the end products of the presented scheme of complex processing of organic waste.

The thermochemical processing of organic waste is of the highest scientific interest among all the fuel production stages. Thermochemical processing involves a series of interrelated processes of heat and mass transfer, complicated by chemical transformations, consisting of many parallel reactions in
which endothermic processes with the flow of thermal energy at the beginning of the process are replaced by exothermic reactions [2].

The works of V.N. Kozlov, V.I. Koryakin, A.N. Koryakin, A.N. Kisliitsin, V.N. Pialkin, A.K. Slavyanskiy, V.I. Yagodin, E.A. Lebedev, N.I. Bogdanovich, R.G. Safin, Yu.L. Yuriev, D.A. Ponomarev, A.N. Grachev, C.H. Bamford, C.Di Blasi, P.S. Maa, C. Briens, F. Thurner, D. Meier are devoted to the issues of thermochemical processing of wood materials.

Despite the large number of scientific works, there are no uniform methods for calculating technological processes and devices for continuous pyrogenic processing of organic waste due to the increased complexity of the processes in the field of thermal decomposition of organic matter.

2. Materials and methods

Studies were carried out using the unit for organic waste processing (Figure 2) [3].

![Figure 2. The unit for organic waste processing.](image_url)

The unit consists of a vertical retort 1 in which organic waste is transported due to gravitational forces through the zones of heating, drying, pyrolysis, activation, cooling with their transformation into
activated carbon, further through the system of the resulting gases separation, the burning device, the
gas cleaning system, recuperative heat exchangers. Cooling of the finished product occurs in 2 steps. In
the zone of the first stage of cooling 4, where in the lower part, at a height of 15-20% of the total coal,
there is a collector 19, through which water is supplied to cool the coal to a temperature of 90-100 °C,
and the upper volume of coal, 80-85 %, cooled by the formed water vapor, which, in turn, overheats to
a temperature of 800 °C. Next, the humidified and cooled activated carbon is directed to the
accumulation zone 5. When the coal is filled in the accumulation zone 5, the vacuum valve 8 is opened
and the contents are dropped into the zone of the second cooling stage 6. Then the vacuum valve 8 is
closed and the vacuum pump 20 is turned on. When the residual pressure reaches 3-6 kPa in the second
stage of cooling 6, the cooled and dried activated carbon is moved by opening the vacuum valve 9 to
the unit of unloading of activated carbon 7 and transferred to the capping by a belt conveyor. In the
activation zone, the interaction of water vapor with coal residue results in the generation of generator
gas, which is converted into electrical energy depending on the type of waste being processed, using an
internal combustion engine (ICE) or fuel cells (FC). Liquid fuel is released from pyrolysis gas - bio-oil
and non-condensing combustible gases, which are burned in the furnace of the pyrolysis zone [4,5].

3. The process modeling

The temperature field in the technological zones of the unit is determined by the heat transfer equation
[6,7], which describes the change of material temperature in time along the layers. For a one-dimensional
layer, it can be written as:

\[ \rho_i \cdot c_i \cdot \frac{\partial T_i}{\partial t} = \frac{\partial}{\partial h} \left( \lambda_{ef} \cdot \frac{\partial T_i}{\partial h} \right) + q_i, \]  

(1)

\( \rho_i \) is the layer bulk density, kg/m\(^3\); \( c_i \) is the heat capacity of the filling layer, J/(kg·K); \( \lambda_{ef} \) is the efficient
heat transfer coefficient of layer, W/(m·K); \( h \) is the particle coordinate in the layer, m; \( q_i \) is the specific
heat flow determined by the heating of the processed waste and the occurring chemical reactions, J/m\(^2\)·s:

\[ q_i = q_h + q_{chem}, \]

where \( q_h \) is heat outflow for the heating of material, J/m\(^2\)·s; \( q_{chem} \) is heat outflow (intake) due to the
chemical reactions, J/m\(^2\)·s.

The initial temperature in the layer \( T_{ini} \) is determined by the final material temperature after the
previous zone, the current temperature at the boundary of the material layer is determined by the
temperature of the heat transferring surfaces.

If we consider biomass as organic waste, then at a temperature of more than 180 °C, its
 thermochemical decomposition begins. This is accompanied by the formation of coal, steam-gas mixture
and a loss of biomass mass.

The change in mass per unit volume for each of the listed components can be written as follows [8,9]:

- For biomass

\[ \frac{\partial \rho'_{biomass}}{\partial t} = -k_{biomass} \cdot \rho'_{biomass} \]  

(2)

- For coal

\[ \frac{\partial \rho'_{coal}}{\partial t} = \phi \cdot k_{biomass} \cdot \rho'_{biomass} \]  

(3)

- For steam-gas mixture

\[ \frac{\partial \rho'_{sg}}{\partial t} = (1 - \phi) \cdot k_{biomass} \cdot \rho'_{biomass}. \]  

(4)

\( \rho'_{biomass} \) is the specific mass of biomass, kg/m\(^3\); \( \rho'_{coal} \) is the specific mass of coal, kg/m\(^3\); \( \rho'_{sg} \) is the
specific mass of steam-gas mixture in the thermal decomposition zone, kg/m\(^3\); \( k_{biomass} \) is the rate constant
of chemical decomposition of biomass, s\(^{-1}\) [11,12].

The degree of thermal modification is determined by the formula
\[ \phi = \frac{\rho_{coal}'}{\rho_{coal} + \rho_{biomass}}. \]

The change in mass of the steam-gas phase of the pyrolysis zone is determined by the sum of mass flows due to convection and the reactions of thermal decomposition of biomass:

\[ \frac{\partial (w_{biomass} \rho_{biomass})}{\partial t} = -\frac{\partial (w_{g} \rho_{g})}{\partial h} + (1-\phi) k_{biomass} \rho_{biomass}'. \]

where \( \varepsilon \) is the particle porosity, which is determined from, \( m^3/m^3 \)

\[ \varepsilon = 1 - \frac{m_{biomass} (1 - \varepsilon_{biomass})}{m_{biomass}^0}. \]

To determine the velocity of the gas flow we used Darcy's law:

\[ w_{g} = \frac{K_p}{\mu_{g}} \frac{\Delta P}{H}, \]

where \( \mu_{g} \) is the gas dynamic viscosity, Pa·s; \( K_p \) is the gas permeability of the particle, which is calculated according to the formula:

\[ K_p = (1-\phi) \cdot K_{biomass} + \phi \cdot K_{coal}. \]

The heat outflow during the thermal decomposition of biomass affects the temperature change of the layer. When calculating, we assume that the temperature of the biomass particles does not deviate from the temperature of the resulting pyrogas, and the gas and solid phases are in thermodynamic equilibrium.

The temperature of the particle is determined from the equation of energy conservation for the particle:

\[ (c_{coal} \rho_{coal} + c_{biomass} \rho_{biomass}) \frac{\partial T_p}{\partial t} = \frac{\partial P_p}{\partial t} \left( \lambda_p - \rho_{g} c_{g} w_{g} - \rho_{s} c_{s} \right) + q_{chem}. \]

\[ q_{chem} = q_0 \cdot (p_{biomass} \cdot \rho_{biomass}) \]

where \( \lambda_p \) is the particle heat transfer coefficient, W/(m·K); \( q_0 \) is the specific heat of the chemical reaction, J/kg; \( w_{g} \) is the speed of steam-gas mixture, m/s; \( \ell \) is the current coordinate in the particle, m.

The rate constant of a chemical reaction is determined in accordance with the Arrhenius law:

\[ k_{biomass} = k_{biomass}^0 \cdot \exp \left( \frac{-E_a}{RT} \right), \]

where \( k_{biomass}^0 \) is the pre-exponential factor, s\(^{-1}\); \( E_a \) is the activation energy, J/mole [13,14].

Initial conditions for solution of the equations (2÷5) and (7) will have the following form:

\[ \rho_{biomass} = \rho_{biomass}^0; \quad \rho_{coal}' = 0; \quad \rho_{g} = 0; \quad T_p = T_{ini}; \]

and the boundary conditions for expression (7) will be written as:

\[ T_p \bigg|_{\ell=L} = T_f. \]

The efficient thermal conductivity coefficient in equation (1) depends on the porosity and temperature of the layer \( \lambda_{ef} = f(\varepsilon, T_f) \), its value is determined experimentally [15].

The coefficient of thermal conductivity for a particle in equation (7) is defined as the sum of the thermal conductivities of biomass, coal and volatile substances, taking into account the degree of pyrolysis and the heat emission through the pores:

\[ \lambda_p = (1-\phi) \cdot \lambda_{biomass} + \phi \cdot \lambda_{coal} + \varepsilon \cdot \lambda_G + \frac{13.5 \cdot c_0 \cdot T^3 \cdot p_{por}}{\psi_G}, \]

where \( c_0 \) is the blackbody coefficient, W/m\(^2\)-K\(^4\); \( \psi_G \) is the emissivity factor of the gas flow; \( p_{por} \) is the size of pores, determined using the formula:

\[ p_{por} = 5 \cdot 10^{-5} \cdot (1-\phi) + 10^4 \cdot \phi \]
4. Results and discussions

During the experiments, the kinetic dependence of the change in the initial mass and slurry output was obtained for the following types of biomass: apricot kernels, sunflower husks, walnut shells, wood flour, sawdust and process chips. The average yield of products by weight was 36.6%, in the slurry it was 45.8%.

![Figure 3. The kinetic dependence of the change in the initial mass of the processed materials.](image)

![Figure 4. The kinetic dependence of the liquid fuel output.](image)

Deviations of calculated data from experimental data for organic waste in the form of biomass does not exceed 18%.

5. Conclusions

A technology has been developed for the processing of organic waste into valuable products: electrical energy, liquid fuels, activated carbon. Mathematical modeling of the process of thermochemical processing of organic waste allows one to determine the yield of liquid and solid fuels, to calculate the specific dimensions of the zone of thermal decomposition in a thermal decomposition unit. As a result of modeling, the kinetic dependences of the change in the initial mass of the processed raw material, the output of coal and liquid fuel were obtained.
References

[1] Slifka M K, Whitton J L 2000 Clinical implications of dysregulated cytokine production. *J Mol Med* 78 74–80.

[2] Brown B, Aaron M 2001 The politics of nature. In: Smith J (ed) The rise of modern genomics, 3rd edn. Wiley, New York, 234–295

[3] Jacobs I S and Bean C P Fine particles, thin films and exchange anisotropy. *Magnetism III*, G. T. Rado and H. Suhl, Eds. New York: Academic, 1963, pp. 271–350.

[4] South J, Blass B 2001 The future of modern genomics. Blackwell, London

[5] Saito Y, Hyuga H 2007 Rate equation approaches to amplification of enantiomeric excess and chiral symmetry breaking. *Top Curr Chem*

[6] Young M 1989 The Technical Writer’s Handbook. Mill Valley, CA: University Science.

[7] Zowghi D et al 1996 A framework for reasoning about requirements in evolution. In: Foo N, Goebel R (eds) PRICAI’96: topics in artificial intelligence. 4th Pacific Rim conference on artificial intelligence, Cairns, August 1996. Lecture notes in computer science *Lecture notes in artificial intelligence* 1114 157.

[8] Sadrtdinov A R, Sattarova Z G, Prosvirnikov D B, Tuntsev D V 2015 Modeling of thermal treatment of wood waste in the gasifiers // Proceedings of 2015 International Conference on Mechanical Engineering, Automation and Control Systems, MEACS 2015. 7414914.

[9] Tuntsev D V 2015 The mathematical model of fast pyrolysis of wood waste 2015 Int. Conf. on Mechanical Engineering, Automation and Control Systems (MEACS) pp 1-4.

[10] DI BLASI C 1996. Heat, momentum and mass transport through a shrinking biomass particle exposed to thermal radiation. *Chemical Engineering Science* 51(7) 1121-32.

[11] Timerbaev N F The development of experimental setups and experimental studies of the process of energy-technological processing of wood *IOP Conference Series: Materials Science and Engineering* 142(1) 012096.

[12] Timerbaev N F 2011 Modeling the process of direct-flow gasification of wood waste *Bulletin of Kazan University of Technology* 7.

[13] Chung S-T, Morris R L 1978 Isolation and characterization of plasmid deoxyribonucleic acid from Streptomyces fradiae. In: Abstracts of the 3rd international symposium on the genetics of industrial microorganisms, University of Wisconsin, Madison, 4–9 June 1978.

[14] Mettler M S 2012 Top ten fundamental challenges of biomass pyrolysis for biofuels *Energy Environ Sci* 2012(5) 797-809.

[15] Antal M J 1983 Biomass pyrolysis: a review of the literature. Part I. Carbohydrate pyrolysis *Adv. In solat Energy* 61 – 111.