

Modeling of the Process of Energy-Technological Treatment of Wood Waste by Method of Direct-Flow Gasification

Nail Farilovich Timerbaev, Ruslan Rushanovich Safin,
Rushan Gareevich Safin and Dilara Farilovna Ziatdinova
Kazan National Research Technological University, Russian Federation,
Karl Marx Street 68, 420015 Kazan, Russia

Abstract: The study presents, the description of the method of complex energy-technological treatment of wood waste, allowing us to achieve the maximum efficiency in the process of treatment of moisture wood waste. Experimental research and mathematical simulation of the process of direct-flow gasification of wood waste are realized. Influence of the main operational parameters on the process of gasification is established.

Key words: Mathematical simulation, gasification, thermal decomposition, gas synthesis, energy efficiency

INTRODUCTION

The modern economics of the Russian Federation has a pronounced raw materials and more than half of economics consists of the production and export of hydrocarbons. Share of production of the timber industry complex in the gross national product of the Russian Federation does not exceed 5%. Increase of effectiveness and competitiveness of wood processing plants in the Russian Federation is one of the priorities of the economy development (Safin and Safin, 2012).

One of the factors hindering the development of forestry enterprises is the low level of their technical equipment, leading to the formation of large quantities of wood waste. Every year millions of tons of wood waste are formed at the forestry enterprises of Russia. Under rational economic management wood waste can be used in production of wood-filled composite materials (Timerbaev *et al.*, 2012) or can be utilized with the purpose of getting heat for drying or thermal treatment (Safin *et al.*, 2014). The simplest way of wood waste utilization is their thermal processing by direct combustion for getting the heat energy. More complicated but more efficient methods are the methods of conversion of wood waste in liquid or gaseous state with obtaining products that are in demand in the chemical and other industries. One of the products which can be obtained by direct-flow gasification of wood wastes is a gas synthesis that is widely used in the chemical industry.

Applied and developed now-a-days layerwise gasificators are focused mainly on getting the thermal energy and mostly produce generator gas, saturated with

nitrogen, water vapors and polluted by products of dry distillation and wood pyrolysis. There are different types of gasificators which ensure better quality of generating gas but they work either under great overpressure or under high temperatures which complicates their instrumentation and as a result, their cost. It makes the processing of wood waste unprofitable in small woodworking factories.

In addition, >70% of the total masses of waste wood of forestry enterprises had high humidity that greatly complicated their energy-technological processing, as the humidity was the main parameter limiting almost all the processes of thermo chemical processing of wood (Timerbaev *et al.*, 2012).

These factors determine the actuality of development of technologies for the complex energy-technological processing of waste wood which would allow obtaining the thermal energy for technological needs of forestry enterprises, generating gas as fuel for existing boiler units or gas synthesis, suitable for further production of variety of chemical products in the conditions of small woodworking enterprises (Timerbaev *et al.*, 2012).

To solve this task it is necessary to create the technological solutions founded in science that allow obtaining the final products of the required quality. Thus, a comprehensive study of the processes of drying of moisture wood wastes, their processing by the method of direct-flow gasification, development of methods of calculation and instrumentation of technological processes of complex treatment of wood waste are an urgent task.

MATERIALS AND METHODS

Chemical processes at thermal decomposition of wood are a complex of chemical transformations of thermal degradation of high-molecular compounds, consisting of a great number of elementary interactions.

Analysis of existing technologies of layerwise gasification of waste wood showed that gasification included interrelated processes of wood waste heating, drying, pyrolysis, combustion and chemical conversion of combustion products into the generating gas. The sequence of the processes depends on the method of gasification which in turn depends on the requirements of generating gas. For the production of generating gas, burned directly in the waste heat boiler, countercurrent or cross flow is applied. For getting the more pure generating gas which can be applied for combustion in internal combustion engines for example or can be used, as a chemical raw material countercurrent regime is applied.

Timerbaev (2011) states that the technology of direct-flow gasification is one of the most promising methods for realization in conditions of small woodworking enterprises now-a-days. The process of complex energy-technological treatment of wood waste, presented in the research of Timerbaev (2012) was developed on the basis of modern views of the influence of temperature on the properties of wood of heat and mass transfer, complicated by parallel proceeding chemical reactions, as well as of sorption-kinetic, thermal and chemical properties of wood.

The scheme of the developed process of energy-technological treatment of moisture wood waste with the preliminary drying by method of direct-flow gasification is presented in Fig. 1.

According to the scheme wood waste arrives at the camera of pre-drying 1. Then dried wastes are divided into 2 streams, the main part goes into the gasificator 2 and the other part goes into the furnace 3 for the production of the heat-carrier. Other input flows in a recycling system for the moisture wood waste is air which serves, as an oxidizer in the gasificator and combustion chamber and as the heat-carrier in the heat exchanger 4 in the production of chemical products 5 made from gasification products. On the logout of system of wood waste treatment researchers have new chemical products, exhaust fluid and ash. The interrelated processes of drying, pyrolysis, combustion and recovery are taking place within this system.

Baker *et al.* (1984), showed in his research the mechanism of thermal decomposition of wood components on the 2 final products, charcoal and volatile gases. The mechanism is presented in Fig. 2.

Decomposition of hemicelluloses occurs in 2 stages, the 1st stage hemicellulose is decomposed into gases and intermediate leavings on the 2nd stage intermediate leavings are decomposed on gas and coal. Cellulose and lignin are decomposed on gas and coal within 1 stage. Mass fraction for hemicellulose, cellulose and lignin depends on the species of wood.

Taking into account the adopted mechanism the change of mass per unit volume for each of the above

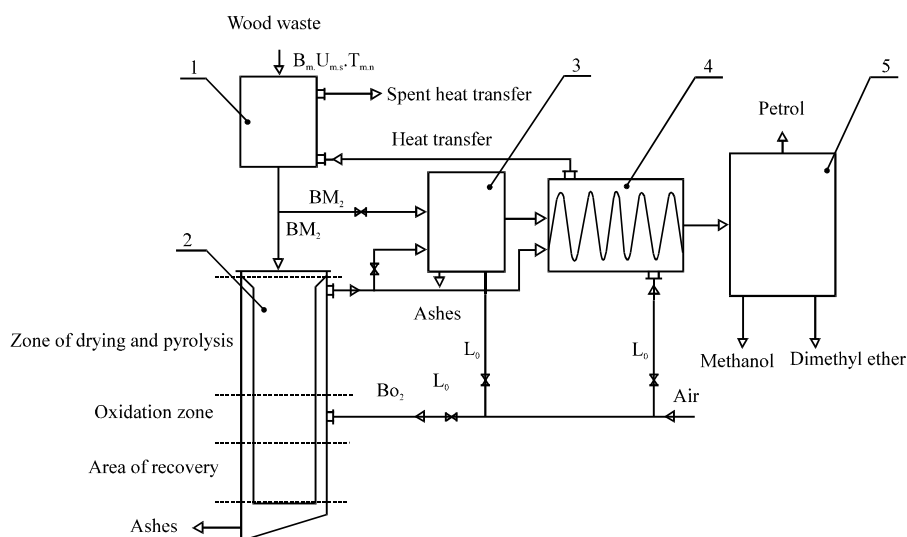


Fig. 1: Structural scheme of energy-technological complex of treatment of wood waste with the use of direct-flow gasification

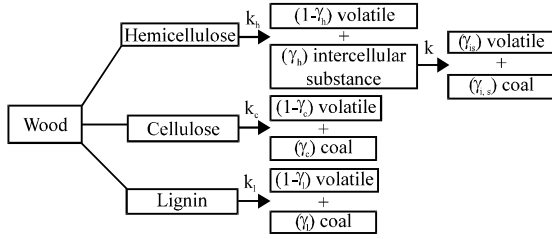


Fig. 2: Mechanism of thermal decomposition of wood components

components will be written, as the equations of chemical kinetics (Galgano and Blasi, 2003). For hemicellulose:

$$\frac{\partial m_h}{\partial \tau} = -k_h \cdot m_h \quad (1)$$

$$\frac{\partial m_{i.s.}}{\partial \tau} = \gamma_h \cdot k_h \cdot m_h - k_{i.s.} \cdot m_{i.s.} \quad (2)$$

For cellulose:

$$\frac{\partial m_c}{\partial \tau} = -k_c \cdot m_c \quad (3)$$

For lignin:

$$\frac{\partial m_l}{\partial \tau} = -k_l \cdot m_l \quad (4)$$

The heat of thermal decomposition of wood can be written in the form:

$$q_x = q_h \cdot (-k_h \cdot m_h + \gamma_h \cdot k_h \cdot m_h - k_{i.s.} \cdot m_{i.s.}) + q_c \cdot (-k_c \cdot m_c + q_l \cdot (-k_l \cdot m_l)) \quad (5)$$

Equation of mass balance for coal and gas will be written in the form:

$$\frac{\partial m_{coal}}{\partial \tau} = \gamma_{i.s.} \cdot k_{i.s.} \cdot m_{i.s.} + \gamma_c \cdot (-k_c \cdot m_c) + \gamma_l \cdot (-k_l \cdot m_l) \quad (6)$$

$$\frac{\partial (\varepsilon \cdot m_g)}{\partial \tau} = -\frac{\partial (w_g \cdot m_g)}{\partial \ell} + (1 - \gamma_h) \cdot k_h \cdot m_h + (1 - \gamma_{i.s.}) \cdot k_{i.s.} \cdot m_{i.s.} + (1 - \gamma_c) \cdot k_c \cdot m_c + (1 - \gamma_l) \cdot k_l \cdot m_l \quad (7)$$

Assuming that the temperature of a particle is equal to the temperature of generated gas during the pyrolysis and thermodynamic equilibrium is installed in the local volume between the components of the gas and solid phases, the equation of conservation of energy can be written in the form:

$$\left(c_h m_h + c_c m_c + c_l m_l + c_{coal} m_{coal} + c_g m_g \right) \frac{\partial T}{\partial \tau} = \frac{\partial T}{\partial \ell} \left(\lambda_p \frac{\partial T}{\partial \ell} \right) - m_g c_g w_g \frac{\partial T}{\partial \ell} + q_x \quad (8)$$

Coefficient of thermal conductivity depends on the share of the reacted wood and is determined by the expression. This is an agreement with the results obtained by Gronli and Melaaen (2000):

$$\lambda_p = (1 - \eta) \cdot \lambda_m + \eta \cdot \lambda_{coal} + \varepsilon \cdot \lambda_g + \frac{13.5 \cdot c_0 \cdot T^3 \cdot d_{por}}{\psi} \quad (9)$$

The process of combustion of pyrolysis products is described by the equations allowing determining the flow rate needed for combustion air, the temperature of the combustion products and their components.

When considering the recovery process due to the significant influence of convective heat transfer and mass, heat conduction and diffusion gas are neglected. Taking into account the assumptions the equations of conservation of substance for each component of the gas flow and for coal will be written in the form:

$$w_{g-g} \cdot \frac{\partial C_i}{\partial y} = -k_i \cdot C_i \quad (10)$$

$$w_{coal} \cdot \frac{\partial m_{coal}}{\partial y} = -m_{coal} \cdot \sum_{i=1}^z k_i \quad (11)$$

The equation of conservation of energy for the gas flow and coal take the form of:

$$\rho_{g-g} \cdot c_{g-g} \cdot w_{g-g} \cdot \frac{\partial T_{g-g}}{\partial y} = -\alpha_{g-g} \cdot (T_{coal} T_{g-g}) \cdot f + \sum_{i=1}^z (q_i \cdot k_i \cdot (C_{i0} - C_i)) \quad (12)$$

$$\rho_{coal} \cdot c_{coal} \cdot w_{coal} \cdot \frac{\partial T_{coal}}{\partial y} = -\alpha_{g-g} \cdot (T_{coal} T_{g-g}) \cdot f - \sum_{i=1}^z (q_i \cdot k_i \cdot (C_{i0} - C_i)) \quad (13)$$

This is an agreement with the results obtained by Kansa *et al.* (1977) and Havens *et al.* (1972). To solve the system of equations (36-39) the boundary conditions are adopted:

$$T_{coal} \Big|_{y=0} = T_{g-g} \Big|_{y=0}; C_i \Big|_{y=0} = C_{i0}; m_{coal} \Big|_{y=0} = m_{y0} \quad (14)$$

The calculation of the gasification process includes, calculation of the area of thermal decomposition of wood material in the absence of oxygen (pyrolysis), calculation of combustion process of pyrolysis products and calculation of the recovery zone of gasification process. An optimization problem of calculating the gasification process is to determine elevation zones of pyrolysis, combustion and restore linked together in such a way that the quantity and quality of coal formed in the zone of pyrolysis satisfy a number of gases produced in the oxidation zone, so that there were no carbon dioxide, water vapor or unreacted carbon at the exit from the zone of recovery.

RESULTS AND DISCUSSION

To develop the effective instrumentation of the process of the energy-technological treatment of wet wood waste with the use of the method of direct-flow gasification, the theoretical and physical modeling of the main processes accompanying gasification is needed.

Figure 3 shows the experimental installation for research of process of direct-flow gasification of wood waste. Experimental setup consists of a series-connected gasifiers 1, afterburners of generator gas 2, heat exchanger 3, purification system of flue gases in the form of absorber 4 and module of control and registration data 5.

Heterogeneous processes in the recovery zone of the reactor gasification are investigated on the installation and the effect of input parameters of the process of direct-flow gasification of wood waste is determined.

The simulation was performed for waste wood of pine with the thickness 0.01 m with the initial temperature of particles $T_p = 25^\circ\text{C}$ to achieve the degree of saturation $\varphi = 0.95$ by drying agent (Razumov *et al.*, 2013).

For increase of efficiency of energy-technological treatment of moisture wood waste, it is appropriate to use the pre-drying of fuel fed into the gasifier due to the heat of exhaust flue gases or the heat from the cooled synthesis gas.

Moisture analysis of flue gases, depending on the temperature and moisture content of the waste has shown that despite the large amount of moisture contained in flue gases they have a sufficient capacity of absorption and can be used as a drying agent.

As a result of studies, it is established that the optimum time is the time necessary for the drying agent (flue gas) to reach the level of the saturation coefficient close to the value of 0.95, as a result of drying of wood waste. A longer stay of flue gas in the drying hopper is undesirable, as the process of condensation of flue gases at the surface of cold wood particles coming from the boot gateway begins.

The experimental and calculated curves of decrease of the mass of wood substances from the temperature of the process in pyrolysis zone are presented on Fig. 4.

The dependence of the structure of generating gas from the humidity of wood waste is presented on Fig. 5. As evident from the data dependency, increase of waste moisture leads to increase of formation of carbon dioxide and water vapor and to reduction of carbon monoxide and hydrogen.

The content of hydrogen in generating gas has the maximum value when the humidity values are in the range of 18-22%. However with a further increase of moisture

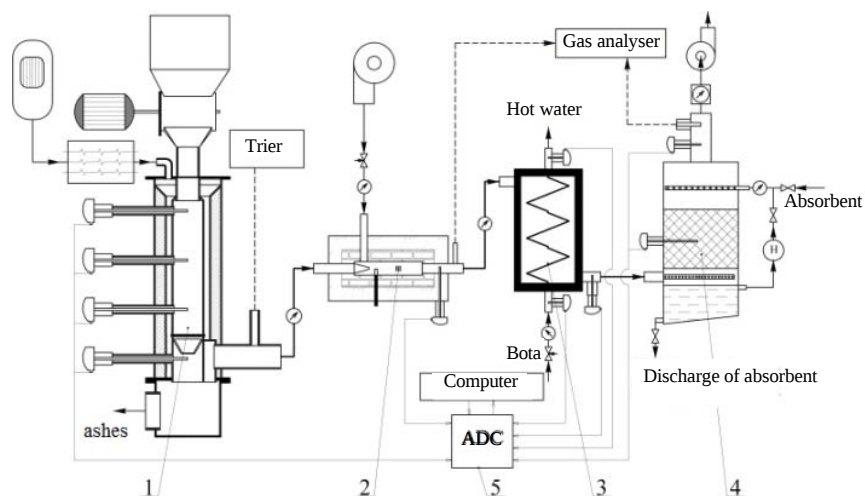


Fig. 3: Scheme of the experimental installation for research of process of direct-flow gasification of wood waste

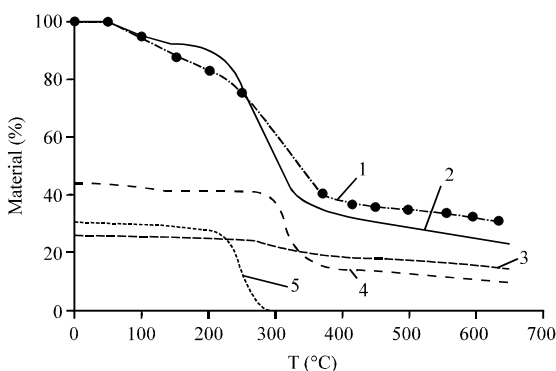


Fig. 4: Dependence of the mass loss from the heating temperature: 1: Material; 2: Material; 3: Lignin; 4: Cellulose; 5: Hemicellulose

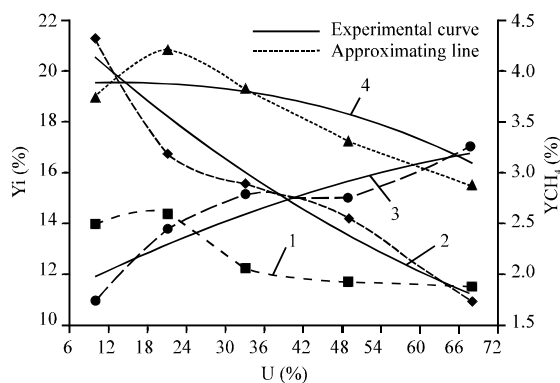


Fig. 5: Dependence of the composition of generating gas from waste moisture: 1: CH_4 ; 2: CO ; 3: CO_2 ; 4: H_2 ; ■, ●, ▲ and ◆ are points describing the experimental values

content of waste, the amount of hydrogen decreases, as a result of reduction of the temperature in the area of recovery.

The consumption of the oxidant into the combustion zone also impacts on the generating gas. The increase of consumption of oxidant to the value of the excess air coefficient of 0.7 leads to increase of temperature in the reducing zone of gasifier and consequently to increase of the content of combustible components of carbon monoxide and hydrogen and to decrease of the share of unrecovered carbon dioxide gas generator. This is explained by displacement of the equilibrium constants of endothermic reactions of recovery of carbon dioxide and water vapor in the direction of formation of hydrogen and carbon monoxide at higher temperatures. Concentration of hydrogen and carbon monoxide in generating gas increases owing to the growth rate of chemical reactions in the areas of combustion and recovery by increasing temperature.

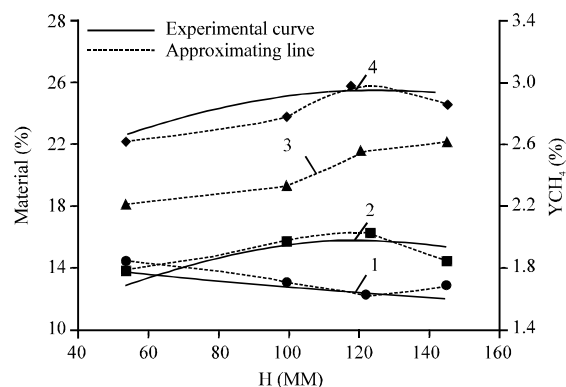


Fig. 6: Dependence of the structure of generating gas from altitude of recovery zone: 1: CO_2 ; 2: H_2 ; 3: CH_4 ; 4: CO ; ■, ●, ▲ and ◆ are points describing the experimental values

The influence of the content of volatiles in coal in the area of recovery on the composition and heat of combustion of generating gas is also determined on installation for research of the process of direct-flow gasification of wood waste. The content of main combustible components of generating gas while increasing the volatile in the corner from 5-24% increases, after that the calorific value of generating gas increases. However, experiments show that a further increase in the volatile coal leads to the formation of undecomposed pitch in the generating gas.

The influence of height of recovery zone on parameters of generating gas is analyzed on install that is presented on Fig. 6. The research results show that with increasing of altitude zone of recovery to 125-135 mm content of combustible components in the generating gas increases. However, further increase in height (over 135 mm) is accompanied by decrease of calorific value of generating gas due to the reduced amount of carbon monoxide and methane, associated with decreasing temperature in the end of recovery zone and flowing of reverse reactions. The content of hydrogen increases slightly.

The concentration of combustible components in the generating gas increases up to the values of filtration rate equal to 7.4 m sec^{-1} , followed by a decrease of concentrations of combustible components. This can be explained by the fact that owing to increase of the rate of filtration to specific values the thickness of the boundary layer around the particles of coal reduces that leads to the increase of concentration of dioxide of carbon on the surface of the coal particles and as a consequence to the increased speed of reduction reactions. However, the excessive increase in the rate of filtration of gasification

agent leads to leakage of CO₂ and H₂O by coal particles that reduce the concentration of CO and H₂ in the generating gas.

Reduction of fractional composition of coal in the recovery zone leads to an increase of the rate of recovery of carbon dioxide which is consistent with the general laws of chemical kinetics.

CONCLUSION

Thus in the course of mathematical modeling and experimental investigations the parameters of the processes of drying, pyrolysis and direct-flow gasification, significantly affect the chemical composition and calorific value of the received generating gas were determined.

REFERENCES

- Baker, E.G., L.K. Mudge and D.H. Mitchell, 1984. Oxygen/steam gasification of wood in a fixed-bed gasifier. *Ind. Eng. Chem. Process Design Dev.*, 23: 725-728.
- Galgano, A. and C. Di Blasi, 2003. Modeling wood degradation by the unreacted-core-shrinking approximation. *Ind. Eng. Chem. Res.*, 42: 2101-2111.
- Gronli, M.G. and M.C. Melaaen, 2000. Mathematical model for wood pyrolysis comparison of experimental measurements with model predictions. *Energy Fuels*, 14: 791-800.
- Havens, J.A., H.T. Hashemi, L.E. Brown and J.R. Welker, 1972. A mathematical model of the thermal decomposition of wood. *Combustion Sci. Technol.*, 5: 91-98.
- Kansa, E.J., H.E. Perlee and R.F. Chaiken, 1977. Mathematical model of wood pyrolysis including internal forced convection. *Combust. Flame*, 29: 311-324.
- Razumov, E., R. Safin, S. Barcik, M. Kvietskova and K. Romelevich, 2013. Studies on mechanical properties of composite materials based on thermo modified timber. *Drvna Industrija*, 64: 3-6.
- Safin, R.G. and R.R. Safin, 2012. Prospects of development of timber industry complex of Tatarstan on the basis of scientific developments of the departments of forestry profile of KNRTU. *Woodworking Ind.*, 3: 22-27.
- Safin, R.R., R.R. Khasanshin, A.R. Shaikhutdinova and A.V. Safina, 2014. Research of heating rate while thermo modification of wood. *World Applied Sci. J.*, 30: 1618-1621.
- Timerbaev, N.F., 2011. Integrated energy-technological processing of waste wood with application of direct-flow gasification. *Kazan National Research Technological University*, pp: 248.
- Timerbaev, N.F., 2012. Mathematical description of the process of thermal processing of wet wood waste by method of direct-flow gasification. *Bull. Kazan Technol. Univ.*, 1: 101-105.
- Timerbaev, N.F., R.G. Safin, A.R. Hisameeva and T.D. Ishakov, 2012. Improvement of techniques and technologies of gasification of moisture wood waste. *Kazan National Research Technological University, Kazan*, pp: 95.