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Modeling the Power Plant Operation to Optimize the Technological and Design Parameters of the Gas Generator Unit

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Abstract: The purpose of the study is to provide a theoretical basis for the energy balance distribution in the gas generator unit to implement the mathematical model of the technological process of the power plant when working on small dairy farms. The optimal operation mode with minimum wood fuel consumption is revealed in the power plant with the gas generator unit. The dependence of energy consumption on the number of dairy farm cows and on the type of wood fuel is determined. The results of process modeling of the power plant allow optimizing the design and technological parameters of the gas generator unit. The optimal operating parameters of GGU on a dairy farm for 100 head of cattle are determined: the diameter of the GGU boiler d_b = 0.46 m, the GG speed in the cooling coil $\upsilon_{c.ci}$ = 37 m/ssc, the diameter of the water storage tank $d_{w.t.}$ = 0.58 m.

Key words: Energy balance, gas generator unit, process modeling, integrated operation mode, wood waste, GGU boiler

INTRODUCTION

In the Russian Federation, the switching of regional power industry to local renewable energy resources based on biomass wastes can be viewed as creating a missing link in the energy supply system: a decentralized energy generation system that operates at the level of distribution networks. The same problem is typical for other major countries of the world: China, Germany, Ukraine, USA, Kazakhstan, etc. Plant waste in the agriculture and forestry of Russia is a strong raw material resources base which can serve as a real basis for the use and development of an independent network of alternative energy. The ability of the raw material resources to renew determines the stability of the energy system and is its undisputed advantage. For the waste utilization, gas generator units are used. The existing gas generator units have disadvantages that affect the quality and quantity of energy production which largely determine the plant efficiency.

Singlitico *et al*. (2017) studies the gasification modeling of food waste. The study includes parametric optimization of food waste gasification. This mathematical model minimizes the cost of electricity production and maximizes energy production (Singlitico *et al*., 2017).

Sahraei *et al*. (2016) conducted an experimental theoretical study of petroleum coke gasification. The composition and flow rate of dry gas, temperature distribution, conversion and formation of pollutants taken from experimental tests and relevant calculations were used to test the predictability of the gasification model in a gas generator unit. This mathematical model makes it possible to predict the operation mode of the gas generator in different conditions.

Vascellari *et al*. (2015) study the modeling of coal gasification. The removal of volatiles during coal gasification is modeled with empirical two-stage competing models whose parameters are calibrated on the pre-processing stage with the help of the advanced pyrolysis models of CPD, FG-DVC and flashchain. The results of advanced pyrolysis models are first tested on true data of volatile outputs obtained at high pressures and heating rates in the experiments on wire reactors.

Donskoy *et al*. (2017) implement a mathematical model to describe the solid fuel conversion in the gasification reactors with a fixed bed and an entrained flow. The proposed models differ from the known ones in such a way that the general problem is reduced to solving a number of less complex sub-tasks one by one for certain stages of the physico-chemical process. This approach allows to significantly reduce the computational effort for

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the algorithms obtained and to preserve the physical content of the model due to the possibility of simplifying the macrokinetic equations. The model is made with the use of the software system CFD-Modeling (COMSOL Multiphisics).

Dubinin *et al*. (2017), Dubinin and Mavrin (2016) consider the problem of insufficient pyrolysis temperature of coal which leads to a reduced efficiency. The researchers propose to supply additional heat to the combustion chamber of the gas-generator unit by the circulating flow of an inert dispersed agent of heat transfer. The experimental data of temperature and gaseous product composition are in good agreement with the simulation results based on the proposed kinetic gasification model.

Seydhosseini *et al*. (2016) analyses the technology of wood pyrolysis in order to obtain a high-quality generator gas for the internal combustion engine of a mobile power plant. He proposes the design of the pyrolysis plant with the active zone of the revolver type which provides uniform wood pyrolysis and its technical characteristics.

Tahmassebpour (2017) study the methods of integrated energy-technological processing of wood waste which allows to achieve maximum efficiency in this process. Experimental research and mathematical modeling of the process of the direct gasification flow of wood waste are carried out. The influence of the main operating parameters on the gasification process is determined.

Lv *et al*. (2014) made experiments on biomass catalytic gasification based on the response surface methods and developed Design-Expert Software. These experiments were carried out in a steam atmosphere and a reactor with two layers. According to the results the gasification temperature and the k-based catalyst content in the gasification layer have a significant effect on the efficiency of the carbon conversion and the hydrogen yield while the content of the Ni-based catalyst in the reforming layer has a significant effect on the gasification reactions. Also, the use of layer transformation has increased the efficiency of carbon conversion by 4.8% while the yield of hydrogen has reached a relative growth of 50.5%.

Hernandez *et al*. (2010) tested three types of biomass fuels (grape pruning and grape sawdust waste) and fossil fuels (a mixture of coal and coke). The results obtained show that the reduction of the fuel particle size leads to a significant improvement of the gasification parameters. The thermochemical characteristic of the obtained ash residue shows a sharp increase in fuel conversion for particles <1 mm in diameter which may be suitable for use in conventional entrained gasifiers. Significant differences between the thermochemical behavior of biomass fuels and that of a coal-coke mixture were revealed, especially in the evolution of the H_2/CO ratio with spatial time, mainly due to the catalytic effect of coal coke ash. The reaction temperature and spatial time have a significant effect on the H_2/CO ratio (the importance of each of these parameters in relation to the temperature) and this value does not depend on the size of the fuel particles.

In these studies mathematical models for the development and improvement of the gas generator unit are considered. The modeling of solid fuel gasification is used. The studies were conducted by means of simultaneous thermal analyses to describe the pyrolysis kinetics of wood and charcoal gasification. For these analyses the original methods of measurements interpretation were developed. They included methods for the technical analysis of fuels and for determining the parameters of the detailed kinetics and pyrolysis mechanism. All gas generator units used by the researchers are aimed at producing only generator gas. However, the development of complex power units for the production of thermal, mechanical and electrical energy as well as their rational distribution depending on the technological production processes are not considered.

Purpose of study: To provide a theoretical basis for the operating parameters of the gas generator unit in order to implement the mathematical model of the energy balance in the energy supply of the technological processes of the dairy farm and to optimize the design and technological parameters of the gas generator unit.

MATERIALS AND METHODS

The gas generator unit was developed at Bashkir State Agrarian University on the basis of an automobile gas generator unit (2017, 2018). The developed unit took into account all the shortcomings of the installations considered above as well as it is aimed not only at the generator gas production but also at the production of thermal energy in the form of heated water.

In Fig. 1 there is the scheme of the power plant with the upgraded gas-generator unit for use in the production activities of the summer dairy farm where there is a need for electricity, heat, mechanical units drive, etc. in different time intervals in accordance with the technological process. This power plant with a gas generator unit can be used for operation in different modes: for the generation of heat, electrical and mechanical energy both separately and together.

The generator gas production takes place in the boiler (6) where various wastes are loaded through the

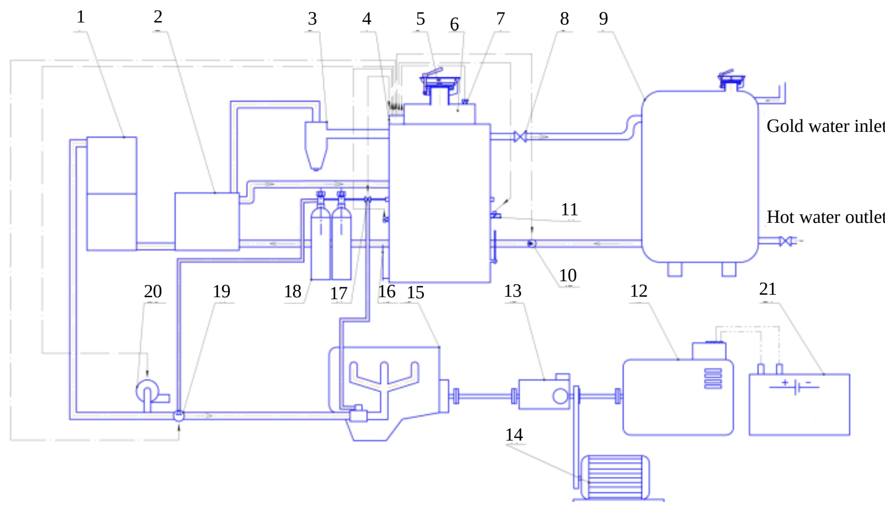

Fig. 1: The general scheme of the power plant: 1) Fine filter; 2) Generator gas cooling system; 3) Coarse filter; 4) Electronic Control Unit (ECU); 5) Loading hatch; 6) Boiler; 7) Temperature sensor; 8) Shut-off valve; 9) Tank for heated water; 10) Water pump; 11) Electrically controlled damper; 12) Electric generator; 13) Reduction gear; 14) Milking machine drive; 15) Internal combustion engine; 16) Unloading hatch; 17) Solenoid valve; 18) Gas gathering cylinders; 19) Compressor device; 20) Accelerating fan and 21) Rechargeable battery

loading hatch (5) and during the combustion with an insufficient air supply there occurs a thermal decomposition of wood. At the initial stage after the fuel is ignited, the gas from the boiler (6) is withdrawn by the accelerating fan 20, until a stable flow of the generator gas is formed. After that the fan (20) is turned off and the Generator Gas (GG) is withdrawn by the operation of the Internal Combustion Engine (ICE) (15) or the compressor gas gathering device (19). If necessary the purified GG can also be collected in the gas-gathering tank (18) by the compressor gas gathering device (19) with the possibility of its further use for the ICE (15).

The generator gas leaves the boiler (6) and enters the coarse filter (3) where it is cleaned of condensate, resins and coarse particles. Then, the generator gas enters the cooling system (2) and at the final stage passes through a fine filter (1). In the ICE (15) the generator gas is already cooled to a temperature of 20, ..., 50°C. When the internal combustion engine operates through the output shaft of the reduction gear (13), the torque is transmitted to the electric generator (12) orto the drive (14) of the mechanical energy consumer.

During the operation of the GGU, a large amount of heat is produced which is used to heat the heat exchanger. To do this, the boiler (6) is equipped with a water jacket which is connected through a pipeline system to the water pump (10) and the water storage tank (9) for use by consumers. When the valve (8) is open, the water circulation in the system starts. The circulation speed is regulated by the water pump (10). After the water temperature in the tank (9) reaches the set value, the pump (10) is turned off by the control unit (4) and the valve (8) is closed. The heated water can be used for the working needs through the water channel.

The proposed design is multifunctional and it can be used for power supply of remote dairy farms in the drying process of agricultural products industrial heating, stationary drive of mechanical devices, etc.

Taking into consideration all mentioned above the aim of the study was to model the operation of the power plant based on the production processes of a small dairy farm.

To develop a gas generator unit, it is necessary to determine the technological parameters of production, namely, energy costs.

Figure 2 gives a general graphical representation of the daily energy needs of various power installations of the summer dairy farm (2016).

Electrical energy is converted into mechanical energy to drive the vacuum pump of the milking machine into thermal energy to heat water and other devices including the refrigeration unit in accordance with the production process. These restrictions were the basis for the development of the mathematical model of the energy balance to determine the rational operation modes of the definite units and the installation as a whole.

The boundary conditions used in the mathematical model of the energy balance of the power plant also, included the cattle population, the number of shifts, the average air temperature, etc.

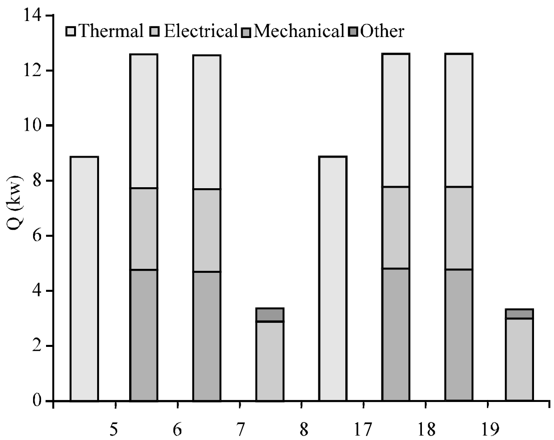

Fig. 2: Energy balance of a dairy farm per 100 head of cattle

The heat balance equation together with the accepted restrictions of technological operation process of a dairy farm is in general as follows:

$$Q_{p.p.} = \sum Q_{unit.} + \sum Q_{loss.} \quad (1)$$

Where:

$Q_{p.p.}$ = The amount of heat produced by the power plant (kJ)

$\sum Q_{unit.}$ = The amount of heat used (kJ)

$\sum Q_{loss.}$ = The amount of thermal losses

$$\sum Q_{unit} = Q_1+Q_2+Q_3+Q_4 \quad (2)$$

where, Q_1-Q_4, the amount of energy consumed, respectively for the mechanical, thermal (water heating), electrical energy and battery charging (kJ).

The operation time interval of the power plant $[0;\tau]$ was divided into n parts by the points $0 = \tau_0<\tau_1<, \dots, <\tau_n = \tau$. The volume of the gas produced by the gas generator unit at time intervals $\Delta\tau_k = [\tau_{k-1};\tau_k]$ per unit of time (productivity, m^3/h) is indicated by (k = 1, ..., n). The corresponding value of the gas volume entering the storage device at the time interval Δτ_k is indicated by V^{gg}_k. If Q^{gg}_k is negative, it means that the gas is taken from the storage tank and enters the ICE. As a result, $V^{p.p.}_k$-V^{gg}_k cubic meters of generating gas are supplied to the engine per unit of time in the interval $\Delta\tau_k$. The amount of energy produced by the engine by burning 1 m^3 of the generator gas is indicated by μ_1.

The operation time interval of the power plant $[0;\tau]$ was divided into n parts by the points $0 = \tau_0<\tau_1<, \dots, <\tau_n = \tau$. The volume of the gas produced by the gas generator unit at time intervals $\Delta\tau_k = [\tau_{k-1};\tau_k]$ per unit of time (productivity, m^3/h) is indicated by $V^{p.p.}_k$ (k = 1, ..., n).

The power consumption of milking machines is indicated by P^{mm}_k for $\tau\epsilon\Delta\tau$. The generator receives a capacity $\mu_1(V^{p.p.}_k-V^{gg}_k)$ P^{mm}_k. The amount of energy produced by the generator is indicated by μ_2.

Let P^{el}_k be the consumed power of electrical energy ($P_{battery}$, $P_{refrigerator}$, $P_{lightning}$, P_{pump}) for $\tau\epsilon\Delta\tau$. Then, if the value P^{el}_k is negative, the electrical energy is taken from the battery by consumers. As a result, we obtain the equality:

$$Q'_{unit} = \left[\mu_1\left(V^{p.p.}_k-V^{gg}_k\right)-P^{mm}_k\right]\mu_2-P^{el}_k \quad (3)$$

Let us set the task of minimizing costs provided that all technological requirements are met. The costs function takes the form of the total volume of the produced generator gas for the entire time interval $[0; \tau]$:

$$F = \sum_{k=1}^{n}\left(V^{p.p.}_k \times \Delta\tau_k\right) \quad (4)$$

where, $\Delta\tau_k = \tau_k-\tau_{k-1}$. Let the heat energy in quantity of Q_2 be transferred to the water through the heat exchanger by the time τj. Let τ_3 denote the amount of thermal energy transferred by the heat exchanger to the heated water per volume unit of the produced generator gas. Then, the following restriction must be satisfied:

$$\tau_3\sum_{k=1}^{j}\left(V^{p.p.}_k.\Delta\tau_k\right) \geq Q_2, j = 1, \dots, n \quad (5)$$

RESULTS AND DISCUSSION

As a result, we obtain a linear programming problem and use standard Mathcad procedures to solve it. Of all the options for the power plant operation (obtaining energy separately without accumulating energy, obtaining only thermal and electrical energy, combined energy production), this mathematical model allows us to calculate the energy balance of the power plant (Fig. 3) in which the consumption of wood fuel is the lowest.

On the basis of the data obtained, it is possible to provide the theoretical basis for the rational energy distribution (according to its types) of the power plant operating on a dairy farm. The best operation mode of the plant is the mode of combined power generation (thermal and gas generating, thermal and mechanical, thermal and electrical) and its storage without any losses. The energy consumption in a combined power generation mode with

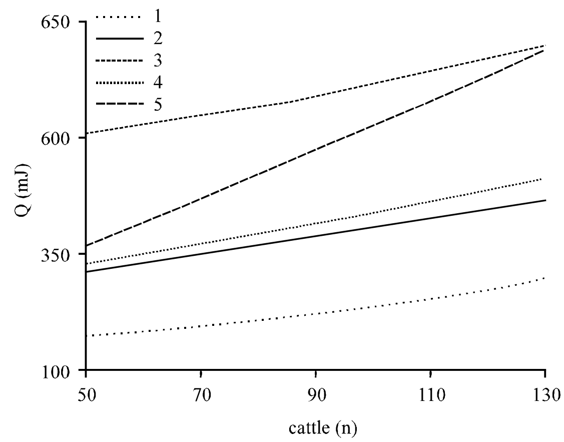

Fig. 3: Energy consumption of the power installation in different operating modes: 1) Combined power generation in the ideal mode; 2) Combined power generation with losses; 3) Mode of only thermal and electrical energy production with energy storage ; 4) Separate mode of energy generation and 5) Mode of eneergy production without its storage

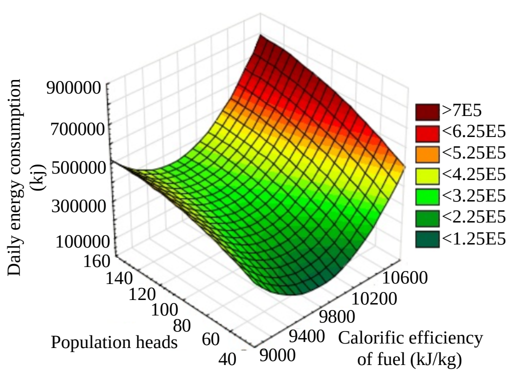

Fig. 4: Energy consumption Q of the power plant according to the cows number n and the type of wood fuel used $Q_{low\ calorific\ value}$

losses ranges from 383,450-745,380 kJ depending on the cows number. The power plant operating in this mode has a high efficiency by combining the generation of various types of energy.

According to the model obtained Fig. 4 shows the energy balance of the power plant Q depending on the type of wood fuel used $Q_{low\ calorific\ value}$ and the cattle number of the dairy farm n_{cows}.

Figure 5 presents the results of numerical studies of the energy balance distribution in the gas generator unit on a dairy farm for 100 head of cattle.

In general, the heat energy consumption is 491598.3 kJ (54 kg of birch wood waste) per one working day. At the next stage, research was conducted to develop a model for optimizing the design and technological parameters (Fig. 6) of the gas generator unit. The parameters to be optimized are: the diameter of the GGU boiler (d_{bi}), the water temperature at the boiler outlet (t''_{boi}), the diameter of the coil (d_{ci}), the gas flow rate in the cooling coil ($\upsilon_{c.ci}$) and the diameter of the hot water tank (D_{ti}). The optimization criterion is the reduced costs C_p rub./(kW•h).

Using heat and mass transfer laws for the design scheme in Fig. 6, the following equations were derived. Temperature gradient of the boiler water jacket wall from the inside:

$$\frac{dt_{wall1}}{dh_b} = t'_{w.b.} - \frac{k_1}{\alpha_1}\cdot\left(t'_{g.b} - t''_{w.b}\right) \quad (6)$$

Where:

- α_1 = The heat transfer coefficient from the water jacket wall to the water (W/(m^2•k)
- $t''_{w.b.}$ = The water temperature in the boiler (°C)
- k_1 = The heat transfer coefficient from the gas to the water jacket wall (W/(m^2•K)
- h_b = The height of the GGU boiler wall covered by the GGM

The temperature gradient of the water jacket wall from the side of the gas jacket:

$$\frac{dt_{wall\,2}}{dh_b} = t'_{g.b} - \frac{k_1}{\alpha_1}\cdot\left(t'_{gas.b} - t''_{w.b}\right) \quad (7)$$

Where:

- $t'_{gas.b}$ = The temperature of the gas in the GGU boiler (°C)
- α_2 = Heat transfer coefficient from the gas to the wall (W/(m^2•k)

The gradient of the boiler wall temperature from the side of the water jacket:

$$\frac{dt_{wall3}}{dh_b} = \left(\frac{\alpha_3.t'_w + \lambda_b}{b_d}.t'_b\right) / \left(\alpha_3 + \frac{\lambda_b}{b_b}\right) \quad (8)$$

Where:

- α_w = Heat transfer coefficient from the wall to the water
- t'_w = Current water temperature in the boiler from top to bottom (C)
- λ_b = Thermal conductivity coefficient of the boiler wall W/(m•K)
- b_b = Wall thickness of the boiler (m)
- t'_b = Current boiler temperature relative to the GGU boiler height (°C)

The gradient of the current temperature of the boiler relative to its height, t'_b:

Cycle	I	II		III	IV	V	VI	VII		VIII	IX	X
Time, h	5	6	7	8	9	10	17	18	19	20	21	22- 3
Water heating, kJ	28385	combining					28385	combining				
Gas (GG), kJ	18954						18954					
Mechanical energy (MM), kJ		94678						94678				
Refrigerator, kJ		-64284		32142,9				-64284		32142,9		
Recharging battery, kJ				15197	47339	-32065				15197	47339	
Night lighting, kJ												8040

-Water heating; - Gas; - Mechanical energy; -Refrigerator; -Recharging battery -Night lighting;

Fig. 5: Graphical representation of the experimental results of energy distribution in the power installation on a dairy farm for 100 head of cattle

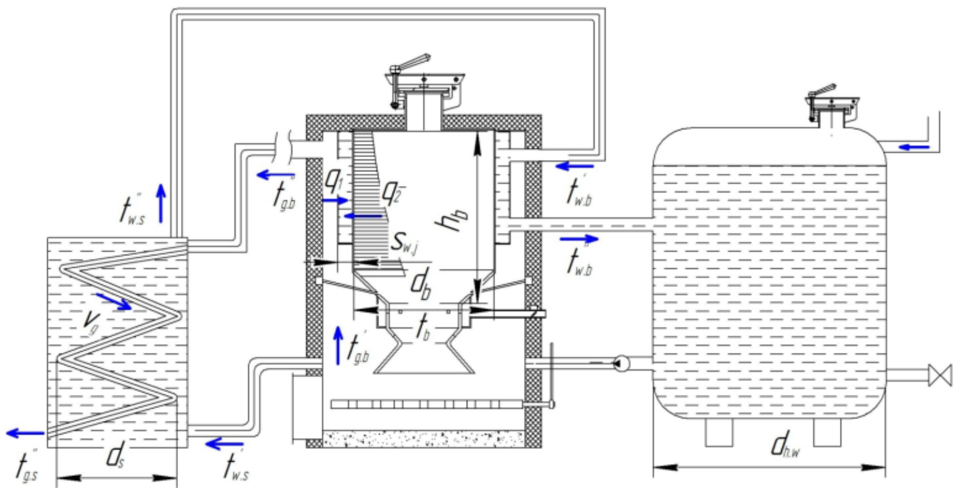

Fig. 6: Calculation scheme of the GGU for the design parameters optimization

$$\frac{dt_b}{dh_b} = \frac{(t_{b.max}-60)}{e^{\left(-60{,}38h'_b+0.052767\,t_{b.max}+ h'_b+18521h'^{0.94}_b\right)}}+60 \quad (9)$$

Where:

$t_{b.max}$ = Maximum temperature in the GGU boiler (°C)
h'_b = Current height of the GGU boiler (m)

The gas temperature gradient in the gas jacket along the height of the GGU boiler, t'_{gas}:

$$\frac{dt'_{gas}}{dh_b} = \pi k_1 . \frac{d_{gasj.}}{q_{ggu}\rho_{gas}C_{gas}}\left(t'_{gas.b}-t''_{w.b}\right)c_i \quad (10)$$

Where:

q_{ggu} = Capacity for the gas production (m^3/sec)
$d_{jasj.}$ = gas jacket diameter (m)
ρ_{gas} = The density of the generator gas (kg/m^3)
C_{gas} = the heat capacity of the generator gas (J/(kg.C)
C_i = Integration step

The gradient of the current gas temperature relative to the GGU boiler height:

$$\frac{dt'_{gas.b}}{dh_b} = t'_{gas.b.max}-\Delta t'_{gas} \quad (11)$$

where, $t'_{gas.b.max}$-maximum gas temperature in the boiler (°C). The water temperature gradient in the water jacket relative to the GGU boiler height:

$$\frac{dt_w}{dh_b} = \frac{\pi.(q_w.c_w).k_1.d_{w.j}.\left(t'_{gas.b}-t_{w.b}\right)+ d_{bi}\cdot\alpha_w\cdot\lambda_{w.j}\left(t'_b-t''_{w.b}\right)}{\left(\lambda_{w.j}+\alpha_w.b_b\right)} \quad (12)$$

Where:

q_w = Mass flow of hot water (kg/s)
c_w = water heat capacity, j/(kg.°C)
$d_{w.j}$ = The diameter of the water jacket (m)
d_b = Diameter of the boiler (m)

Using these Eq 6-12, numerical studies were carried out to optimize the design and technological parameters of the GGU on a dairy farm for 100 head of cattle Fig. 7.

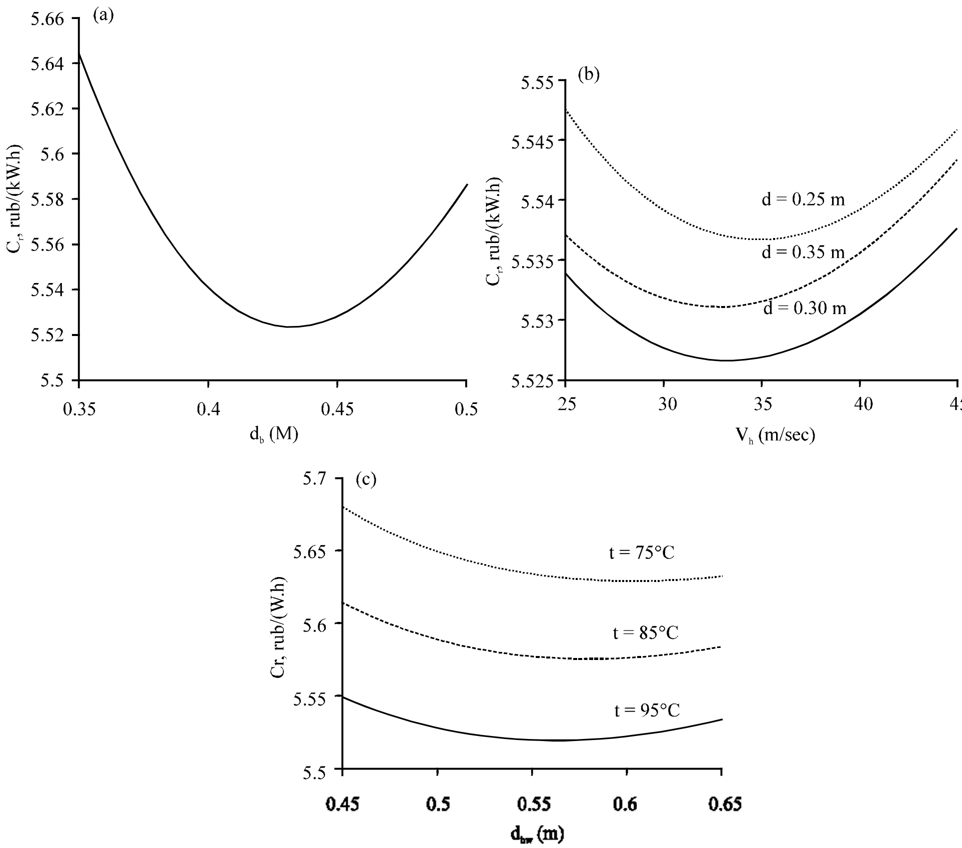

Fig. 7: a): Dependence of the unit costs on the diameter of the GGU boiler: b) GG speed in the pipe coil cooler with different coil diameters and c) The diameter of the hot water tank at different hot water temperatures

CONCLUSION

The proposed mathematical model of the energy distribution in the power plant on a small dairy farm allows calculating the heat balance of energy with the smallest consumption of wood fuel. The theoretical basis for the rational distribution of energy according to its types (thermal, mechanical and electrical) is provided depending on the cattle number of a summer dairy farm.

Mathematical models for the optimization of technological and design parameters of the GGU are developed. The optimal operation conditions of the GGU on a dairy farm for 100 head of cattle are determined: the diameter of the GGU boiler d_b = 0.46 m, the speed of the GG in the cooling coil $\upsilon_{c.c.i}$ = 37 m/sec with the coil diameter d_c = 0.30 m, the diameter of the water tank $d_{w.t}$ = 0.58 m with the water temperature at the boiler outlet $t''_{w.b}$ = 95°C and when the gap clearance of the water jacket $S_{w.j.}$=0.035 m.

The obtained mathematical models allow us to determine the optimal operation mode of the installation at the power supply of any technological production processes and to model the technological and design parameters depending on the quantitative energy needs.

REFERENCES

Donskoy, I.G., V.A. Shamansky, A.N. Kozlov and D.A. Svishchev, 2017. Coal gasification process simulations using combined kinetic-thermodynamic models in one-dimensional approximation. Combust. Theory Modell., 21: 529-559.

Dubinin, A.M. and S.P. Mavrin, 2016. Coal gasification in a system with a damped circulating fluidized bed. Steel Transl., 46: 764-770.

Dubinin, A.M., V.G. Tuponogov and Y.A. Kagramanov, 2017. Air-based coal gasification in a two-chamber gas reactor with circulating fluidized bed. Therm. Eng., 64: 46-52.

Hernandez, J.J., G. Aranda-Almansa and A. Bula, 2010. Gasification of biomass wastes in an entrained flow gasifier: Effect of the particle size and the residence time. Fuel Process. Technol., 91: 681-692.

Lv, X., J. Xiao, Y. Du, L. Shen and Y. Zhou, 2014. Experimental study on biomass steam gasification for Hydrogen-rich gas in Double-bed reactor. Intl. J. Hydrogen Energy, 39: 20968-20978.

Sahraei, M.H., M.A. Duchesne, R.W. Hughes and L.A. Ricardez-Sandoval, 2016. Experimental assessment, model validation and uncertainty quantification of a pilot-scale gasifier. Ind. Eng. Chem. Res., 55: 6961-6970.

Seyedhosseini, S.M., M.J. Esfahani and M. Ghaffari, 2016. A novel hybrid algorithm based on a harmony search and artificial bee colony for solving a portfolio optimization problem using a mean-semi variance approach. J. Cent. S. Univ., 23: 181-188.

Singlitico, A., K. Dussan, R. O'Shea, D. Wall and J. Goggins *et al*., 2017. Techno-economic optimisation of combined anaerobic digestion and gasification of food waste as part of an integrated waste management and energy system. Proceedings of the 25th European International Conference and Exhibition on Biomass, June, 12-15, 2017, Stockholm, Sweden, pp: 12-15.

Tahmassebpour, M., 2017. Detecting fault location in wireless sensor networks using an exploratory method based on fuzzy logic. Proceedings of the 2017 IEEE 4th International Conference on Knowledge-Based Engineering and Innovation (KBEI'17), December 22, 2017, IEEE, Tehran, Iran, ISBN: 978-1-5386-2641-2, pp: 0465-0469.

Vascellari, M., D.G. Roberts, D.J. Harris and C. Hasse, 2015. From laboratory-scale experiments to industrial-scale CFD simulations of entrained flow coal gasification. Fuel, 152: 58-73.