IRSTI 30.17.33 https://doi.org/10.26577/JPCSIT.2023.v1.i1.02

W. Wojcik

Lublin University of Technology, Lublin, Poland
e-mail: waldemar.wojcik@pollub.pl

BUILDING A MATHEMATICAL MODEL OF THE BIOGAS COMBUSTION PROCESS

Abstract. During the experimental work thermodynamic methods of measuring the flow of water vapor and hydrogen-oxygen mixture on the basis of differential pressure gauges, methods of contact and non-contact temperature measurement in the superheated, permeable layer of biomass, tried and tested standard methods of synthesis gas analysis using chromatograph and flow gas analyzer were used. Proven mathematical models and proven reliable methods were used in mathematical modeling. Research methods include experimental studies to establish the effect of temperature conditions of gasification, properties of feedstock on the qualitative composition and quantitative yield of synthesis gas; modeling process of carbon-bearing substances gasification with the solution of the resulting model by iteration-interpolation method.

Key words: biomass and biodegradable fuels; ATS – automatic control system; TVT – solid types of biomass; TP – technological process; biomass and biodegradable waste; control object; internal combustion engine; Efficiency factor – efficiency factor; circulating fluidized bed; analog-digital converter.

1 Introduction

The intensive development of the industry of Kazakhstan creates a global problem of disposal of liquid and solid organic waste at wastewater treatment plants, which are generated in large quantities. It is very difficult to store and process such waste. In addition, recently the problems of waste management have attracted the close attention of environmentalists and health authorities, who are concerned about the possibility of pollution entering water bodies and spreading pathogens in this way.

Stages of simulation modeling in the study of a complex problem situation. Modeling of the control system is carried out using a system (structural) analysis of complex ACS with the following iterative selection of the parameters of the transfer functions of control objects. [1-2]

A feature of this method is the small initial amount of information and relatively less laboriousness. Structural analysis is used in the early stages of creating a control system to identify the properties of the system, which are determined by its structural features.

Modeling the control system for the process of biogas combustion using structural analysis is divided into stages:

1) Identification of the boundaries of a technological object and its subsystems;
2) Building a graph of subsystems;
3) Development of a simulation model of subsystems;
4) Checking the adequacy of the model of each of the subsystems;
5) Combining subsystem models into an object model.
6) Checking the adequacy of the object model.

Accepted assumptions:

The feedstock is an ideal gas.

The loss of material and energy flows during transportation, heating, cooling is zero. [3-4]

2 Results and Discussion

Depending on how the impact on the object is organized, it is possible to obtain a static or dynamic simulation model. In the event that the values of the random variable at the input of the object change at sufficiently large, not necessarily equal, intervals of time, then by registering the output value of the object after the end of the transient process, it is possible to calculate its static characteristic. Since the static characteristic calculated in such an experiment does not depend on time, its calculation is carried out according to the values of the numerical series supplied to the input of the object and representing a sample of a random variable. To obtain statistically significant characteristics of a static simulation model, a random variable must have predetermined statistical characteristics, which primarily include the mathematical expectation, variance and distribution law of a random variable. When calculating static (but not statistical) characteristics, methods of probability theory, mathematical statistics, and the theory of experiment planning are used. [5-6]

The object under study has two inputs (biogas supply and air supply) and one output (flue gas temperature), the disturbance is steam extraction. We will build a simulation model using the correlation identification method to determine the delay time, and the MATLAB System Identification Toolbox application to build multidimensional simulation models. Figures 1 and 2 show the mutual correlation functions of the fuel and air control channels.

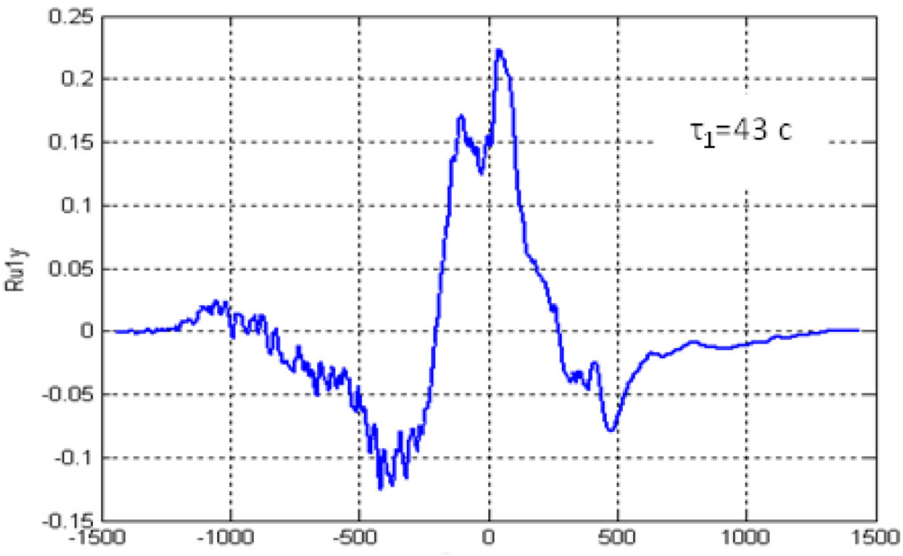

Figure 1 – Mutual correlation function of the fuel channel

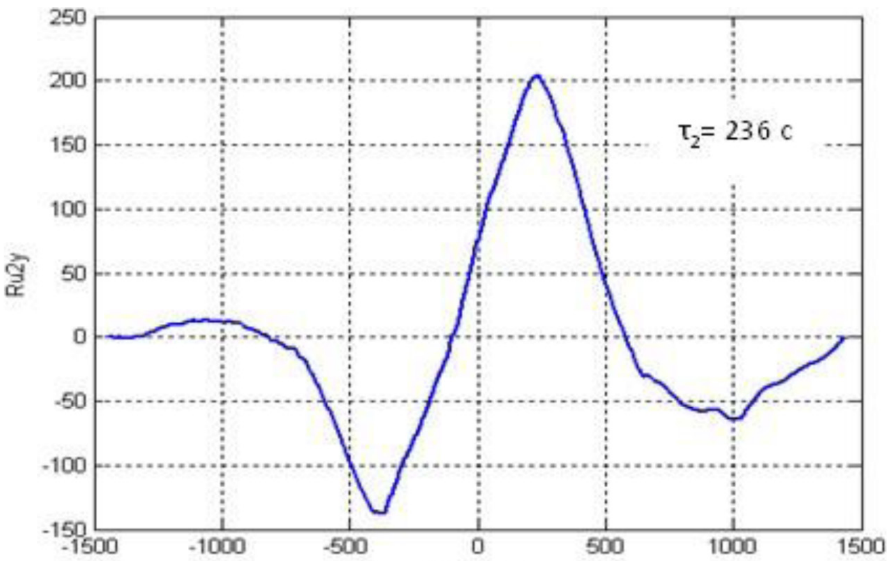

Figure 2 – Mutual correlation function of the air channel

Figure 3 shows the results of fuel path identification.

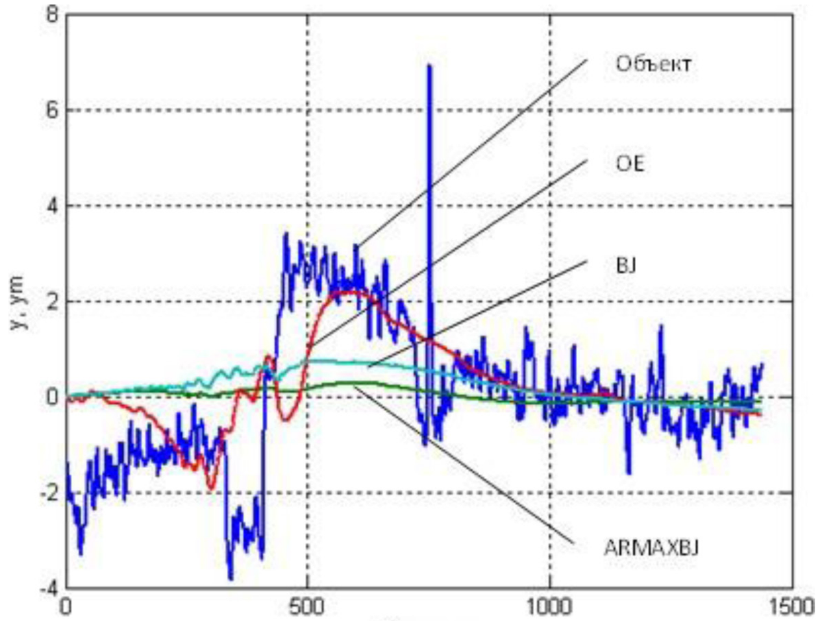

Figure 3 – Output signals of models and object

As seen from the waveforms of the output signals least OE-model gives an error.

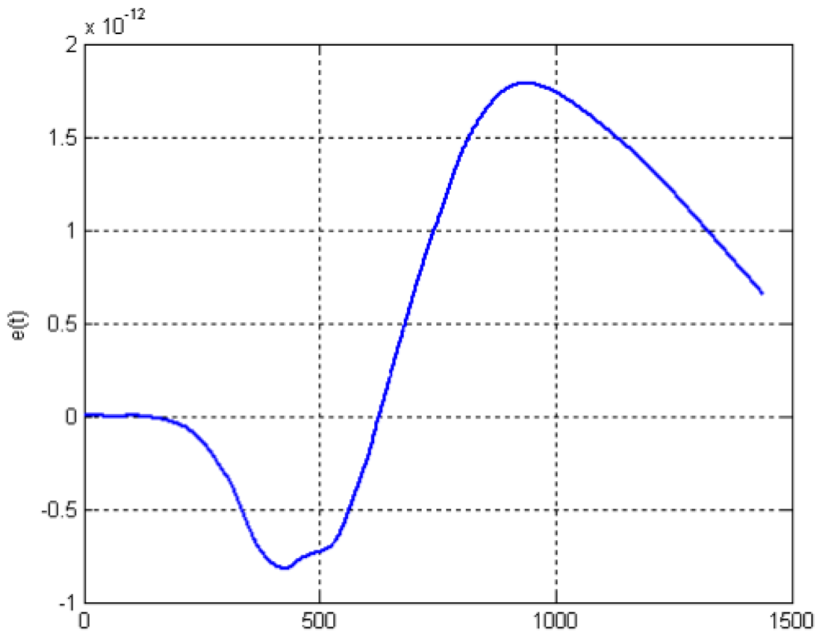

Figure 4 – error Simulation

During the modeling process, as a result of multiple selection, a search step equal to 48.3 m3/h was chosen. Based on the obtained model of the fuel path, the dependence "temperature – fuel – air" (Figure 5) was built, which is in good agreement with a similar experimental dependence.

As can be seen from Figure 5, the use of the developed algorithm ensures stable operation of the system in the region of maximum temperature values.

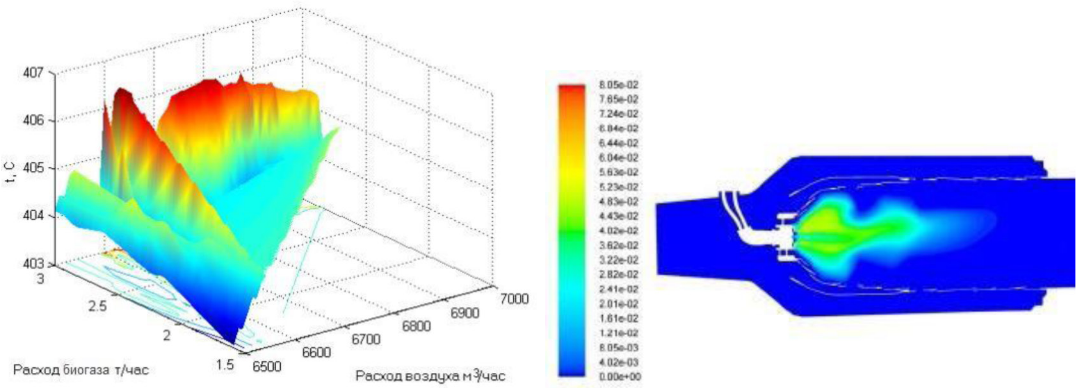

Figure 5 – Gas temperature on the supply of biogas and air

The conducted studies have shown the possibility of organizing the process of biogas combustion in the proposed device. [7-8] Based calculation results, the burner geometry was changed taking into account the shortcomings of previous models:

– the volume of the combustion area and the outlet section of the device were increased, which led to the appearance of a region of return flows and a zone of steady combustion, in general, increasing the completeness of biogas combustion to 60%;

– the redistribution of the oxidizer supply before and after the combustion area was performed, which made it possible to increase the combustion efficiency by 18-22%%

– a tangential air inlet into the mixing chamber was organized, which ensured a stable entry of biogas into the combustion zone and the absence of particles slipping into the oxidizer supply chamber.

In the end, it was possible to develop a vortex burner, the completeness of biogas combustion in which, based on the simulation results, reaches 95%.

The results of the calculation of the final version of the burner are presented in Figures 6-8.

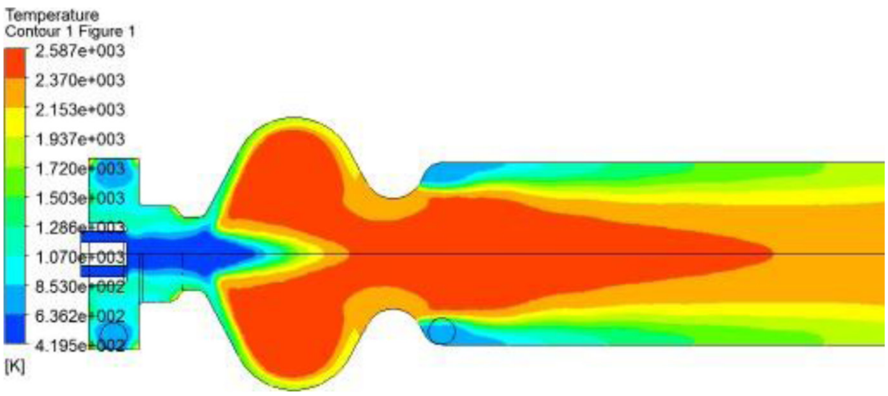

Figure 6 – Temperature distribution in the cross section of the burner with two air inlets at $\alpha = 1{,}3$

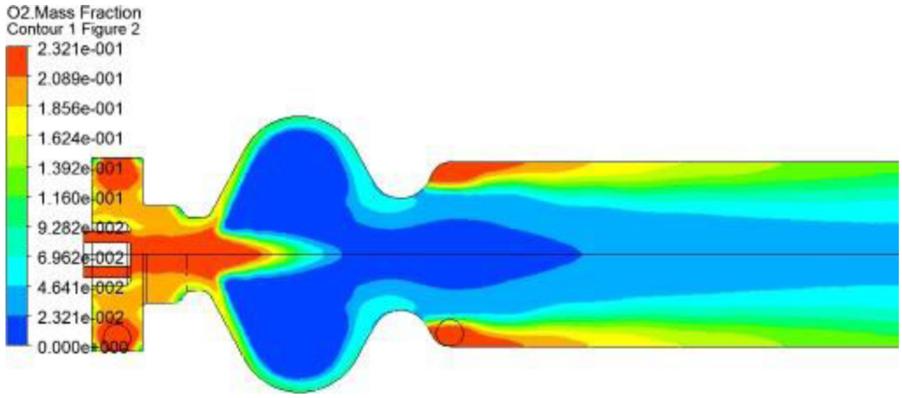

Figure 7 – Distribution of mass concentrations of oxygen in the cross section of the burner with two air inlets at $\alpha = 1{,}3$

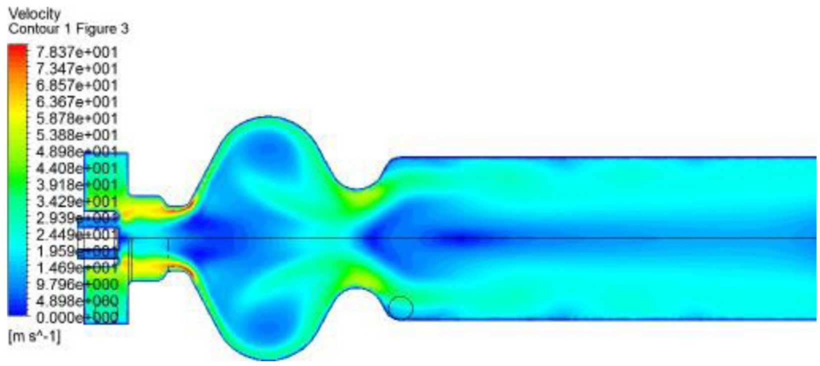

Figure 8 – Velocity field in the burner section at $\alpha = 1{,}3$

The assessment of the completeness of combustion in the developed device was carried out for the supplied biogas. For the biogas released during the combustion process, the pattern of biogas concentrations and its dynamics are analyzed.

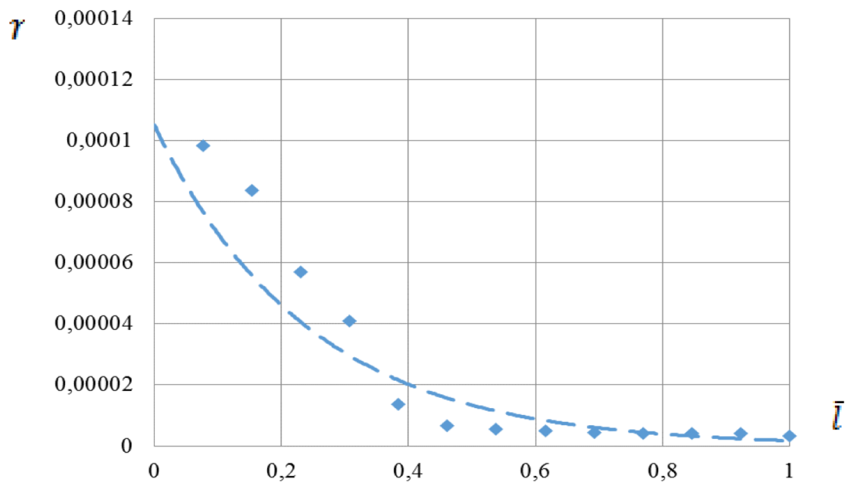

Figure 9 – Volume fraction of biogas along the length of the burner devices

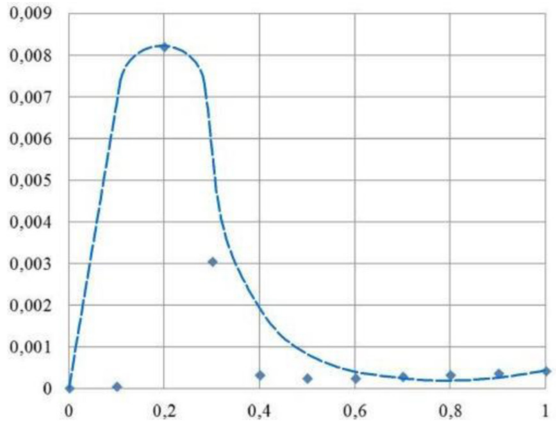

Figure 10 – Mass fraction of released combustible biogas along the length of the burner

For the developed burner, according to the results of calculations, the completeness of combustion of biogas is

$$\eta_{\text{тв}} = 0{,}94 \ldots 0{,}96.$$

Computational fluid dynamics (CFD – Computational Fluid Dynamics) allows you to calculate the processes of biogas flow, heat transfer, chemical reactions and other phenomena that occur in a homogeneous medium, or between phases. CFD can be used to explore new gasifier concepts and geometries and optimize and upgrade existing solutions [9-11]. There is a lot of material in the literature about the use of CFD calculations to model the operation of a gasifier. Most authors propose simplified models (2D), covering only the reduction part of the chamber [12] or a model with arbitrarily allocated volumes of calculations, covering sequentially the heating zones of the layer, biomass drying, pyrolysis, oxidation and reduction of carbonizate [13]. There are several multi-phase models in Fluent that can potentially be used to stimulate the gasification process. In the gas generator there is a big difference in the residence time of the solid layer and biogas, and the whole process must take place in a steady state. The process of gasification, as well as combustion, consists of a complex set of physical and chemical phenomena. Mathematical modeling is an attempt to describe this process, highlighting the following elements: biogas flow through a porous layer (biomass), dispersed phase flow (coal particles), interaction between phases, homogeneous reactions in the gas phase, combustion processes of solids (debiogasification, surface reactions).

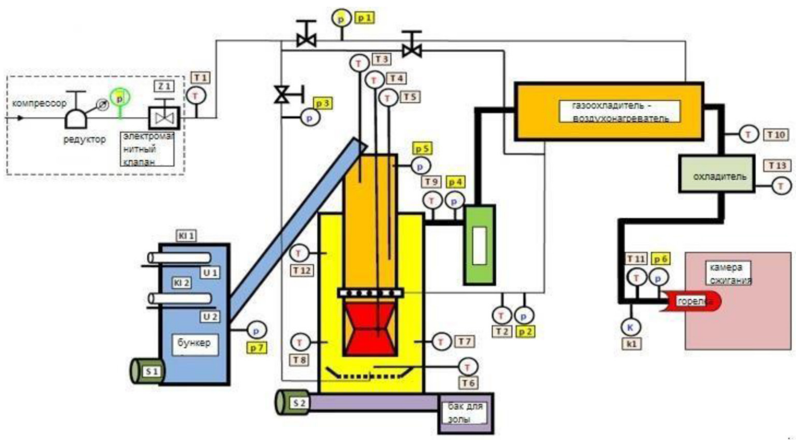

Figure 11 – Technological scheme of the biogas combustion process in a laboratory installation

Figure 12 – Torch of flame obtained by burning biogas in a laboratory installation

Figure 13 – Two-level structure of the automated system for diagnosing and controlling the process of biogas combustion in laboratory conditions of the Lublin University of Technology (Lublin, Poland)

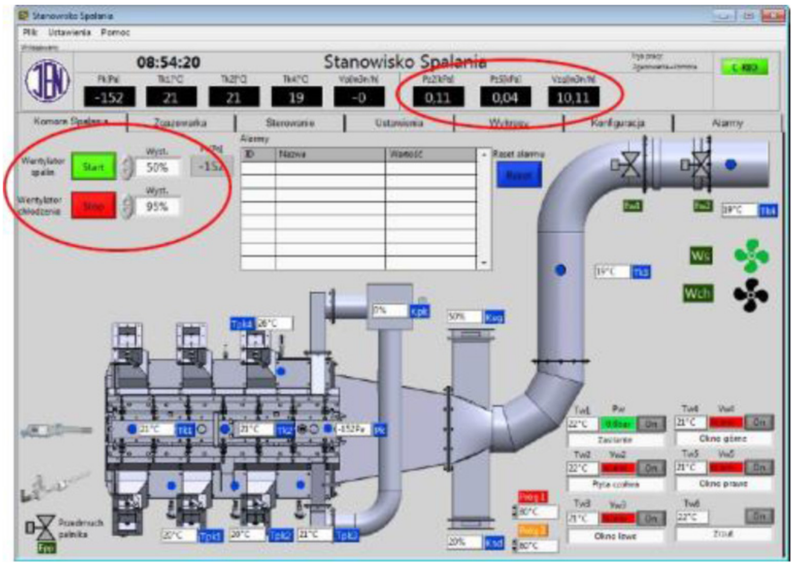

Figure 14 – Video frame "Biogas combustion chamber"

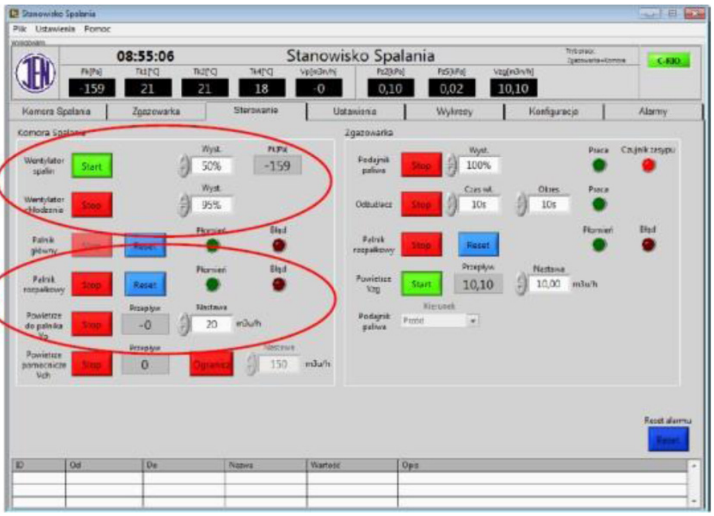

Figure 15 – Video frame “Control”

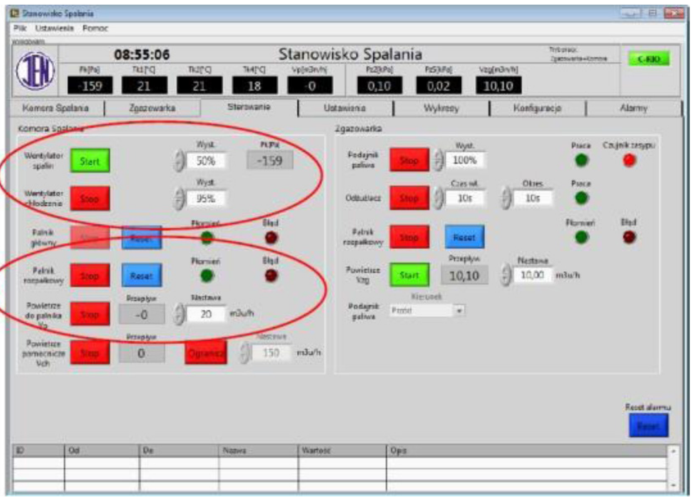

Figure 16 – Video frame “Settings”

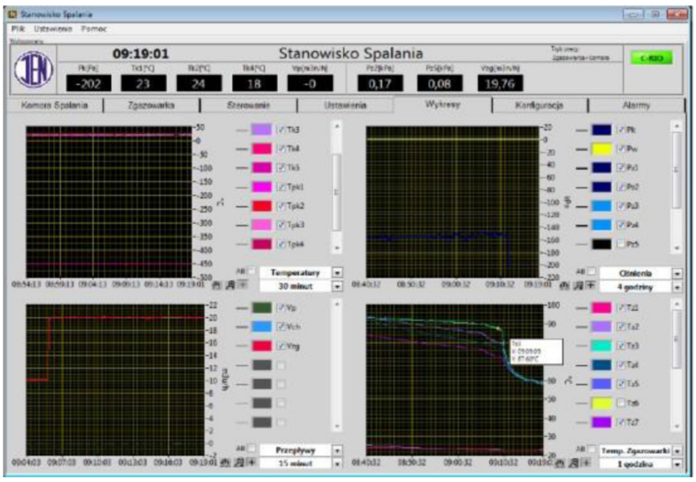

Figure 17 – Video frame “Trends/charts”

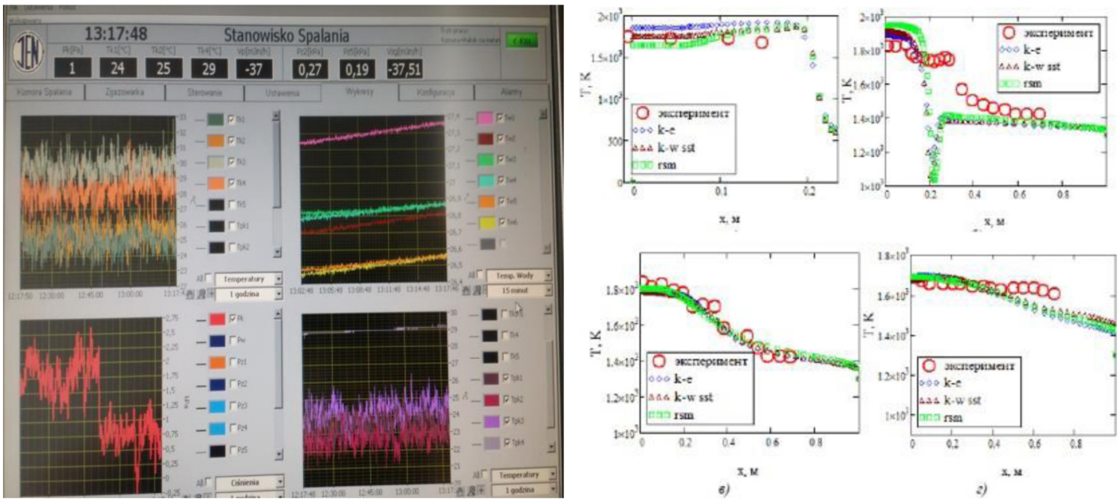

Figure 18 – Temperature profile in the sections of the combustion chamber (a – z =0, b – z = 0.25, c – z = 0.85, d – z = 1.95)

The results of the influence of different turbulence models on the temperature distribution over the sections of the combustion chamber are shown in Figure 18. It's clear that results of calculations with three different turbulence models agree relatively well with each other and with experimental data. This comparison by pulsations speed showed that the best agreement with experiment is observed when using the Reynolds stress model [14]. The results of calculations and comparison with experimental data showed that the selected mathematical model based on the RANS approach and numerical methods for its solution make it possible to correctly describe the processes of heat and mass transfer and combustion of biogas in a combustion chamber with a vortex burner with an accuracy sufficient for engineering problems [15]. To process the data obtained during the experiments the OPUS program was used, which allows plotting spectra and import them into a bitmap. (Figure 18)

Experimental studies were carried out on laboratory equipment, the design of which ensured the receipt of estimated indicators of the working processes of biogas plants under various modes of anaerobic digestion [16-18]. We propose to apply the psychrophilic periodic mode of operation of a biogas plant with a digester of small volume – from 1 m 3 and less – for the following significant reasons: the plants currently produced operate in the mesophilic mode, are equipped with a high-precision automated system; lack of technologies for the mechanization of labor-intensive processes and the processing of produced biogas; pollution of the environment, increasing the level of hazardous effects on human health.

Conclusions

The stages of simulation modeling in the study of a complex problem situation are given. The mathematical model is constructed and the method of calculation of parameters of biomass gasification process is developed. Installation with biomass gasifier was simulated in the computer program Math Lab. A mathematical model of the gasification process in the oxidation and reduction zones was built.

References

1. Turowski L., Is biomass a waste? Environmental Information Center – Ekoportal.pl, 2007.
2. R. Wasilewski, Sobolevski A. Solid Secondary Biogas as Part of a Waste-to-Energy Recovery System, 2009, 28-33.
3. T. Pajak, Domestic Waste Thermal Treatment Systems in Kazakhstan – Conditions, Plans, Implementation, New Energy, 1, 2008, 2-10.
4. A. Sobolevsky, Wasilewski R., Stelmakh S., Use of Solid Secondary Biogas in the Energy Sector, Energy Policy, Vol. 10, Special Issue 2, 2007, 379-389.
5. M. Shinoda, R. Tanaka, Arai N. Optimizing the heat transfer characteristics of a ceramic heatrecirculating burner during methane/air, and gasification/air with low calorific value biogas. Energy Transformation and Control, Vol. 43, 2002, pp. 1479-1491.

6. Reid RD, Schwartz RE. Gasifier assembly for biogas combustion of the calorific value of gases, US Patent 4,323,343,1982.
7. Heat from Biomass in Practice 2008 – Polish Chamber of Biomass, Warsaw – Kielce, 2008.
8. Suzuki T. Biogas burner and method of combustion Iow biogas calorific value, US Patent 5, 447, 427,1995.
9. M. Shinoda, R. Tanaka, Arai N. Optimizing the heat transfer characteristics of a ceramic heatrecirculating burner during methane/air, and gasification/air with low calorific value biogas. Energy Transformation and Control, Vol. 43, 2002, pp. 1479-1491.
10. Turowski L., Is biomass a waste? Environmental Information Center – Ekoportal.pl, 2007.
11. Reid RD, Schwartz RE. Gasifier assembly for biogas combustion of the calorific value of gases, US Patent 4,323,343,1982.
12. Pantangi VK, SC Mishra. Combustion of gaseous hydrocarbon fuels in porous media – a review, progress in the development of energy research, 2006.
13. Turowski L., Is biomass a waste? Environmental Information Center – Ekoportal.pl, 2007.
14. R. Tanaka, M. Shinoda, Arai N. Combustion characteristics of a ceramic heatrecirculatingf burner using Iow-calorific-fuel energy conversion and control, Vol 42, 2001, pp. 1897-1907.
15. M. Shinoda, R. Tanaka, Arai N. Optimizing the heat transfer characteristics of a ceramic heatrecirculating burner during methane/air, and gasification/air with low calorific value biogas. Energy Transformation and Control, Vol. 43, 2002, pp. 1479-1491.
16. Hamamre ZA, S. Diezinger, Talukdar P., von ISSENDORFF V., trimis D. Burning Iow calorific value of gases from landfills and pyrolysis of waste using porous medium gasifier technology. Trans Ichem, Part B, Process Safety and Environmental Protection, Vol. 84(B4), 2006, pp. 297-308.
17. Reid RD, Schwartz RE. Gasifier assembly for biogas combustion of the calorific value of gases, US Patent 4,323,343,1982.
18. M. Shinoda, R. Tanaka, Arai N. Optimizing the heat transfer characteristics of a ceramic heatrecirculating burner during methane/air, and gasification/air with low calorific value biogas. Energy Transformation and Control, Vol. 43, 2002, pp. 1479-1491.