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Modeling the influence of the characteristics of renewable organic materials on the energy performance of the boiler

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Abstract. The object of the modeling is the process of burning organic waste, depending on the nature of the origin of the fuel, its chemical and fractional composition, density and lower calorific value. Processing the results of experimental study using analysis of variance will allow to estimate the variance caused by each factor individually and determine the level of influence of the factors on the output parameters of the process. It is necessary to obtain not only the form of this dependence, relying on the experimental data, but also to assess the influence of each factor on the lower calorific value. The analysis of the obtained dependence shows that the airflow speed and the fractional composition of this fuel have the greatest influence on the efficiency of the boiler plant. Checking the significance of the coefficients showed that all the coefficients of this model are significant. The regression dependencies were obtained that estimate the lower calorific value and the efficiency of the boiler which burns briquettes from organic matter; the analysis of the obtained dependencies was carried out, the significance of the coefficients included in the model was checked; the composition factor has the greatest influence on the lower calorific value.

1. Introduction

Renewable organic materials are beginning to be widely used as fuel in the global energy sector. Organic substances used as fuel can be found in abundance at a short distance from the planned heat generation plant. At the same time, one of the main issues is the technology and mechanism for obtaining thermal energy with maximum efficiency.

Thus, in the works [1-3], the combustion characteristics of fuel briquettes made from organic waste were investigated. The work [4] shows the influence of the composition of fuel briquettes on their thermophysical and mechanical properties. The influence of the composition on the properties of briquettes is assessed by carrying out measurements on the obtained briquettes

Information on the properties of the obtained briquettes is important not only for further improving their properties (increasing strength, calorific value, etc.), but also for choosing boilers where the briquettes will be burned most efficiently, as well as for designing new boilers for burning fuel briquettes of this composition [5].

The analysis of the operation of boilers on briquettes from organic waste shows that their combustion is similar to the fuel recommended by the manufacturer [6]. Moreover, experimental measurements have shown an overall increase in thermodynamic efficiency from 86,73 % to 94,08 % and increase in maximum combustion efficiency from 91 % to 96,2 %, while emissions of CO and NO_x have been significantly reduced.

In addition, an important issue that is reflected in the literature is the study of the briquette combustion process. The rate of the chemical oxidation reaction mainly depends on the oxygen concentration, which, in turn, depends on the density of the briquette. Thus, the properties of the briquette affect the rate and degree of burnup, which is important for the combustion of a certain type of briquettes in various boilers [7].

Numerical modeling of the processes in the boiler is carried out with the help of software (for example, FLUENT). Using software, three-dimensional dynamic models of combustion in the boiler are obtained. Based on the modeling results, the influence of various factors on the efficiency of the boiler operation is determined [8, 9].

Processing the results of the experimental study of the systems using analysis of variance allows for a complex multifactorial process to evaluate the variances caused by each factor separately, to determine the level of influence of the studied technological factors on the output parameters of the process [10].

Analysis of variance makes it possible to answer the question whether the factor under study influences or does not influence the parameters of the product, but it does not allow determining either the degree or the nature of this influence. Correlation and regression analysis can be used to resolve these latter issues.

Experimental planning methods can be widely used in any experimental research, if it is possible to actively influence the experimental conditions, to change the input parameters at will. In this case, the task is to increase the efficiency of researches, i.e. to obtain, with the minimum possible number of experiments, the most information about the process under study in order to describe it with the greatest accuracy.

2. Formulation of the problem

The process of burning fuel briquettes from organic waste depends on many factors, namely: on the origin of the fuel, their chemical and fractional composition, density, lower calorific value, etc. All of these factors are closely interconnected, and in this regard, some difficulties arise in modeling the combustion of renewable organic materials.

3. Theory

The considered aspects of incineration processes of renewable waste fit well into the general strategy of systemic analysis as applied to sufficiently large systems. In this case, mathematical modeling is selected as a method for studying the object, and its main principle is decomposition, i.e. decomposition of a complex (large) system into simpler ones that interact with each other and within the framework of a general model. Despite all the complexity of the proposed way, it seems natural and correct, since it is part of a systematic approach to considering the behavior of large systems [10].

An objective indicator of fuel mass is its lower calorific value, which is directly related to such characteristics as density and strength.

The dependence on these factors can be considered as random and analyzed using probabilistic methods. For effective analysis, it is necessary to identify the relationships between the factors and present them in quantitative form - in the form of a mathematical model:

$$\sigma = \sigma(x_1, x_2, \dots, x_n), \tag{1}$$

where σ – this is the lower calorific value, kJ/kg;

$x_1, x_2, \dots, x_n$ – factors influencing the result.

It is necessary to obtain not only the form of this dependence, based on experimental data, but also to assess the influence of each factor on the lower calorific value.

Based on the analysis of the assessment of the influence of various factors on the lower calorific value, we choose:

x_1 – the ash content, %;
x_2 – the density, kg/m^3;
x_3 – the ratio of the constituents in the briquetting mass, % / %;
x_4 – the relative humidity, %.

From physical considerations, we can assume that the relationship of the expression (1) has the following form:

$$\sigma(b,x) = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n}\sum_{k=i+1}^{n} b_{ik} x_i x_k + \sum_{i=1}^{n}\sum_{k=i+1}^{n}\sum_{l=k+1}^{n} b_{ikl} x_i x_k x_l + \dots + b_{12\dots n} x_1 x_2,,, x_n \quad (2)$$

where b_0– a free term equal to the output at x=0;

b_i – a regression coefficient indicating the influence of the factor on the process;

b_{ij} – regression coefficients that determine the degree of the influence on the interaction process of the factors.

Having determined the regression coefficients of this equation, we will get an idea of the influence of the studied factors on the lower calorific value of the fuel. The regression coefficients are calculated using the following formulas [10]:

$$b_i = \frac{1}{N}\sum_{j=1}^{N} \overline{\sigma}_j\, x_i^j,\ i = 0,..,n,\ b_{ij} = \frac{1}{N}\sum_{j=1}^{N} \overline{\sigma}_j\, x_i^j \dots x_\mu^j,\ i,\mu = 1,2,..,n, \quad (3)$$

where $\overline{\sigma}_j$ – the value of the process mean output in j-variant;

x_i^j – the factor value in j-variant.

At each experimental point we carry out two experiments. To calculate the estimates of the coefficients, we will use the arithmetic mean of these observations for each point $\tilde{y}^i = \frac{\overline{\sigma}^{i1} + \overline{\sigma}^{i2}}{2}$. Further, based on the experimental data, we calculate the estimates of the coefficients by the formulas (3) and obtain the form of the interpolation formula. The last step is to assess the significance of the regression coefficients and check the adequacy of the model.

To assess the significance of the regression coefficients, it is necessary to find their sample variance $S^2[b_i]$. The significance of the regression coefficients is determined by the inequality

$$b_i \succ S[b_i] \cdot t_{cr}(f), \quad (4)$$

where $t_{cr}(f)$ – the Student's coefficient for a given confidence p and the number of degrees of freedom $f = (\nu - 1) \cdot N$.

Thus, the mathematical model of this process can be described quite accurately using the interpolation formula (2), taking into account the assessment of the influence of each of the experimental factors on the target value.

Based on the order of the estimation of the coefficients when using this design, it is possible to draw up an experiment design and obtain an experiment design matrix.

Another equally important task is researches related to the efficiency of the combustion of fuels from renewable organic waste in boiler furnaces.

An objective indicator of the efficiency of using this fuel in the furnaces of boilers of low and medium power is its efficiency (i.e. coefficient of performance), which is directly related to such characteristics as the excess air coefficient, layer height and fractional size.

At the same time, a number of factors influence the final value of the boiler plant efficiency (its coefficient of performance). The dependence of the efficiency on these factors can be considered as random and analyzed using probabilistic methods. For effective analysis, it is necessary to identify the relationships between the factors and present them in quantitative form - in the form of a mathematical model

$$\eta = \eta(\mathrm{x}_1, \mathrm{x}_2, \dots, \mathrm{x}_n), \quad (5)$$

where η – this is the efficiency of the boiler plant, %;

$x_1, x_2, \dots, x_n$ – the factors that influence the result.

Based on the analysis of the assessment of the influence of various factors on the efficiency, presented earlier, we choose the following as the experimental factors:

x_1 – the size of fractions of the fuel briquettes, mm;

x_2 – the excess air ratio in the combustion chamber;

x_3 – the airflow speed, m/s;

x_4 – the height of the fuel layer on the fire-grate, mm.

It is necessary to obtain not only the form of this dependence, based on the experimental data, but also to assess the influence of each factor on the value of the efficiency. From physical considerations, we can assume that relationship (5) has the form of an equation (2).

Having determined the regression coefficients of this equation, we will get an idea of the influence of the studied factors on the value of the efficiency. The calculation of the regression coefficients is carried out according to the formulas (3). The significance of the regression coefficients is determined by the inequality (4).

Let us find an interpolation formula that could be used to describe the dependence of the efficiency on the four factors listed above (without taking into account the pair interactions)

$$\tilde{\eta}(b,x) = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4. \quad (6)$$

Using the above methodology, we will determine the regression coefficients of the equation to study the influence of the determining factors on the efficiency of the furnace.

4. Experimental results

Table 1 demonstrates the design of experiment to study the influence of various factors on the lower calorific value of renewable organic materials and its results. The values of the process outputs were obtained as a result of the experimental and calculated studies.

Table 1. The design of experiment №1.

Planning					The process output
x_0	x_1	x_2	x_3	x_4	Lower calorific value, kJ/kg
+	+	+	+	+	18702.4
+	-	+	+	-	18924.3
+	+	-	+	-	18681.5
+	-	-	+	+	18694.1
+	+	+	-	-	18631.2
+	-	+	-	-	18652.2
+	+	-	-	-	18639.6
+	-	-	-	+	18631.3

The interpolation formula for the dependence of the lower calorific value on the process factors is as follows:

$$\hat{y} = 18708.40 - 30.90x_1 + 32.99x_2 + 56.06x_3 - 29.85x_4. \quad (7)$$

Table 2 shows the design of experiment to study the influence of various factors on the efficiency of the boiler when burning renewable organic materials and its results. The values of the process outputs were obtained as a result of the experimental and calculated studies.

Table 2. The design of experiment №2.

Planning					The output
x_0	x_1	x_2	x_3	x_4	η, %
+	+	+	+	+	82.0
+	-	+	+	-	83.0
+	+	-	+	-	85.0
+	-	-	+	+	81.0
+	+	+	-	-	81.0
+	-	+	-	+	82.0
+	+	-	-	+	82.5
+	-	-	-	-	80.0

Thus, the interpolation formula for the dependence of the boiler efficiency on the process factors has the following form:

$$\tilde{\eta} = 82.06 + 0.56x_1 - 0.06x_2 + 0.69x_3 - 0.19x_4. \quad (8)$$

5. Discussion of the results

The analysis of the obtained dependence shows that the airflow speed and the fractional composition of the fuel have the greatest influence on the efficiency of the boiler plant.

The factor x_3 (composition, that is, the ratio of combustible components in the initial fuel mass) has the greatest influence on the lower calorific value (of all the values under consideration). Moisture, ash and density have almost the same effect on the lower calorific value but to a lesser extent.

Let us check the adequacy of the model and the significance of the quadratic effects in both experiments.

In the first case N = 8, ν = 2. Let us calculate the values of the output variable in points and determine the vector $\hat{Y}$. To check the adequacy of the resulting model, we calculate the estimate of the variances of observation errors, which we calculate using the sum of squares of errors according to

$$S_l = \sum_{i=1}^{8} \sum_{j=1}^{2} \left(\overline{\sigma}^{ij} - \overline{\sigma}^{i}\right)^2 = 13.18 \quad (9)$$

with the number of degrees of freedom $\varphi_2 = N(\nu - 1) = 8(2 - 1) = 8$ according to the formula

$$S^2 = S_l \cdot (\nu \cdot \varphi_2 \varphi)^{-1} = 0.82. \quad (10)$$

$$S = 0.91. \quad (11)$$

Let us find the sum of squares characterizing the inadequacy of the model

$$S_D = \sum_{i=1}^{N} \nu \cdot \left(\overline{\sigma}^{i} - \hat{\sigma}^{i}\right)^2 = 1.65. \quad (12)$$

Hence follows the formula

$$F = (S_D/\varphi_1) \cdot (S_e/\varphi_2)^{-1} = (1.65/1) \cdot (13.18/8)^{-1} = 1.00 \quad (13)$$

In the table of 95 % Fisher–Snedecor distribution [11] we find the value $F_{cr} = 5.32$ for 1-P = α = 0.05. Here α is a given level of significance for testing the adequacy hypothesis. In our example $F = 1.001 \prec F_{cr} = 5.32$.

Thus, the obtained process model is adequate.

Now let us check the significance of the found regression coefficients. To do this, we determine the Student's coefficient at a given level of significance α = 0.05 and with eight degrees of freedom $t_{cr}(f) = 2.306$.

For the variances of the estimates of the coefficients, we obtain

$$S_i^2 = S^2 \cdot N^{-1} = 0.103; \; S_i = 0.321. \quad (14)$$

Here with

$$s_i \cdot t_{cr}(f) = 0.321 \cdot 2.306 = 0.740. \quad (15)$$

Checking the significance of the coefficients showed that all the coefficients of this model are significant. Therefore, the regression equation, taking into account this remark, will remain the same.

Let us check the adequacy of the model and the significance of the quadratic effects in the second experiment. In this case N = 8, ν = 2. Let us calculate the values of the output variable in points and determine the vector $\hat{Y}$. To check the adequacy of the resulting model, we calculate the estimate of the variances of observation errors, which we calculate using the sum of squares of errors according to

$$S_l = \sum_{i=1}^{8} \sum_{j=1}^{2} \left(\overline{\sigma}^{ij} - \overline{\sigma}^{i}\right)^2 = 56 \quad (16)$$

with the number of degrees of freedom $\varphi_2 = N(\nu - 1) = 8(2 - 1) = 8$ according to the formula

$$S^2 = \mathrm{S_l} \cdot (\mathrm{v} \cdot \varphi_2\varphi)^{-1} = 3.5;\ S = 1.871. \quad (17)$$

Let us find the sum of squares characterizing the inadequacy of the model

$$S_D = \sum_{i=1}^{N} \nu \cdot \left(\overline{\sigma}^i - \hat{\sigma}^i\right)^2 = 15.6 \quad (18)$$

Hence follows the formula

$$F = (S_D/\varphi_1) \cdot (S_e/\varphi_2)^{-1} = (15.6/1) \cdot (56/8)^{-1} = 2.23 \quad (19)$$

In the table of 95 % Fisher–Snedecor distribution [11] we find the value $F_{cr} = 5.32$ for 1-P = α = 0.05. Here α is a given level of significance for testing the adequacy hypothesis. In our example $F = 2.23 \prec F_{cr} = 5.32$.

Thus, the obtained process model is adequate.

Now let us check the significance of the found regression coefficients. To do this, we determine the Student's coefficient at a given level of significance α = 0.05 and with eight degrees of freedom $t_{cr}(f) = 2.306$ [11].

For the variances of the estimates of the coefficients, we obtain

$$S_i^2 = S^2 \cdot N^{-1} = 0.4375; \quad S_i = 0.661. \quad (20)$$

Here with

$$s_i \cdot t_{cr}(f) = 0.61 \cdot 2.306 = 1.525 \quad (21)$$

Checking the significance of the coefficients showed that in the second experiment all the coefficients of this model are also significant. Therefore, the regression equation, taking into account this remark, will remain the same.

6. Conclusions

Thus, the analysis of the modeling results allows us to draw the following conclusions:

- the regression dependencies were obtained that assess the lower calorific value and the efficiency of the boiler which burns briquettes from organic matter;
- the analysis of the obtained dependencies was carried out, the significance of the coefficients included in the model was checked;
- factor x_3 (composition, i.e. the ratio of combustible components in the initial mass) has the greatest influence on the lower calorific value (from the considered values). Moisture, ash and density have almost the same effect on the lower calorific value but to a lesser extent;
- the airflow speed and the fractional composition of briquettes have the greatest influence on the efficiency of the boiler plant;
- the adequacy of this model was verified, which showed that the proposed models are adequate, because the errors characterizing the accuracy of the model do not exceed the errors of observations.

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