Algorithm and Software for Controlled Incomplete Combustion Method

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***Abstract* - The article describes the methodology of an experiment to reduce the coefficient of excess air in the furnace in order to find the minimum total harmfulness of combustion products in boiler houses and power plants running on hydrocarbon fuel. A detailed mathematical analysis of pairs of numbers obtained during the experiment is proposed (coefficient of excess air; total harmfulness of combustion products). An algorithm of an automatic control system is proposed that allows implementing the principle of minimal harmfulness of combustion products.**

Keywords — algorithm; emissions; programming; sensor; excess air factor

I. Introduction

It is well known that a decrease of the excess air in a boiler unit combustor leads to reduction of nitrogen oxide emission and, consequently, of a negative impact of boiler houses on the environment. Such an operating mode of boiler units is called controlled incomplete combustion, and this regularity is true for boilers that run on all types of fuel [1]. However, due to a number of reasons, including a lack of well-developed experimental procedure and subsequent mathematically grounded approaches to adjustment of boiling unit performance, controlled incomplete combustion is not widespread. This paper proposes an experimental method, mathematical processing of results, as well as a program that realizes a control algorithm for Arduino UNO controller.

II. Main points

A. Experimental procedure

The experiment is carried out on an industrial boiler unit with rated natural gas consumption. Airflow rate is regulated with a damper, installed on the air duct. Concentration of nitrogen oxide and carbon oxide is measured with a portable gas analyzer, then the dependence of discharge of these harmful gases on the excess air factor is built up in MS Excel (Table 1). The content of oxygen in the flue gases is measured with the same gas analyzer. Values of the excess air factor are calculated by the formula [1]:

$$\alpha = 21/(21 - O_2 - 0.5CO), \qquad (1)$$

where O_2 and CO is the percentage composition of oxygen and carbon monoxide in the flue gases.

A particular value of combustion products harmfulness is determined from the formula [2]:

$$\Pi_i = m_i * (1 - \eta)/(\frac{Q_i^p}{(Q_i^p)_{fe}} * \frac{TLV_{STEL\,i}}{(TLV_{STEL})_{ash}}),$$

where $Q_i^p, (Q_i^p)_{fe}$ is the calorific capacity of the fuel under examination and the fuel equivalent respectively, [MJ/m^3]; $TLV_{STEL\,i}$, $(TLV_{STEL})_{ash}$ are short-term exposure limits (STEL) for the impurity *i* and ash respectively [mg/m^3]; η is the degree of purification of the flue gases from the impurity *i* before their emission to the atmosphere (as fractions of "1").

The total harmfulness is calculated by the formula:

$$I_\Sigma = I_1 + I_2, \qquad (3)$$

where I_1 and I_2 are the particular indices of nitrogen oxide and carbon monoxide harmfulness.

Let us illustrate with a specific example how the data, obtained during the experiment, is proposed to be used (Table 1).

TABLE 1. POSSIBLE VALUES OF THE CONCENTRATIONS OF NITROGEN OXIDE AND CARBON OXIDE IN COMBUSTION PRODUCTS OF A BOILER UNIT, AS WELL AS OF THE TOTAL HARMFULNESS I_Σ

Excess air factor	Concentration of NO_x, mg/m^3	Concentration of CO, mg/m^3	Total harmfulness I_Σ
1.05	120	1000	0.015
1.1	150	400	0.016
1.15	180	100	0.017
1.2	200	50	0.019
1.25	220	0	0.02
1.3	270	0	0.021
1.35	300	0	0.022
1.4	300	0	0.022

B. Mathematical processing

Mathematical processing of the concentration values, presented in Table 1, is aimed at finding dependency of the total harmfulness of combustion products I_Σ=f(α). For this purpose, several regression models – linear, quadratic, power, logarithmic and exponential – are built in MS Excel (or other mathematical resources) by the existing values of α and I_Σ (Table 2).

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It is known that the correlation coefficient is a statistical indicator of the dependence of two random variables. The correlation coefficient can take values from -1 to +1. At the same time, a value of -1 will indicate a lack of correlation between the values, 0 - a zero correlation, and +1 - a complete correlation of values. The average approximation error is the average deviation of the calculated values from the actual ones. A mean approximation error of up to 2% indicates a well-chosen model of the equation.

An average error of approximation is calculated with the use of the resource https://planetcalc.ru/5992. The regression models are compared against each other by correlation and the average error of approximation. The comparison allows to determine the most accurate functional dependency. This very dependency is proposed to be used in a program code for the controller.

TABLE 2. SUMMARY TABLE OF THE REGRESSION EQUATIONS THAT DESCRIBE THE EXPERIMENTAL RESULTS

Type of regression	**Linear pair correlation coefficient R^2**	**Average error of approximation, %**
Linear $y=0.0219x-0.0078$	0.9689	2.0840
Polynomial (degree 2) $y=-0.0286x^2+0.0919x-0.0503$	0.9853	1.4954
Polynomial (degree 3) $y=-0.2424x^3+0.8624x^2-0.994x+0.3884$	0.9958	0.6400
Power $y=0.0141x^{1.4465}$	0.9635	2.1033
Logarithmic $y=0.0044+3.2563\ln x$	0.9772	1.7308
Exponential $y=e^{-5.4189+1.1806x}$	0.9493	2.4856

The Table 2 analysis shows that the lowest value of the linear pair correlation coefficient is observed in the quadratic regression $y=-0.2424x^3+0.8624x^2-0.9939x+0.3884$. It means that this very regression is the most accurate one to describe the dependence of the total harmfulness I_Σ of combustion products on the excess air factor α.

A number of parallel data processing algorithms are known [3].

C. Automatic air damper control system (ACS).

The paper [4] presents a hardware component of the automatic air damper control system (ACS) for the air flow rate in a boiler unit.

This system can be considered as a dynamic system and its parameters can be calculated by the following method [5].

The hardware of the complex is represented by a programmable logic controller (hereinafter - PLC), as an input signal, receiving readings from the content sensor oxygen in flue gases. Analysis of existing methods for measuring acid concentration kind in flue gases showed that the most simple, inexpensive and not requiring complex-maintenance are sensors based on electrochemical principle reaction. An example is the oxygen sensors BOSCH (https: //ru.bosch-automotive.com/ru/parts_and_accessories) installed on most domestic (russian) and foreign cars. The cost of such sensors is about 50 USD.

The ACS, as well as its operation algorithm, are presented in Fig. 1 and 2. The complex is aimed at minimizing the total harmfulness of combustion products of NO_x and CO with simultaneous control (accounting) of their concentrations.

D. Programming of logic controller (PLC)

The paper [3] presents a hardware component of the automatic air damper control system (ACS) for the air flow rate in a boiler unit. The ACS, as well as its operation algorithm, are presented in Fig. 1 and 2.

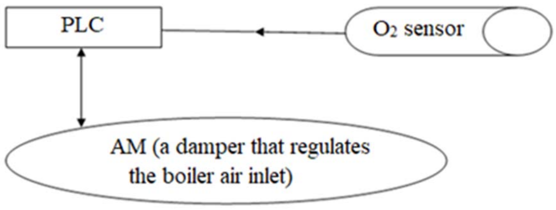

Fig. 1. Block diagram of the ACS hardware component: PLC – programmed logic controller, AM – actuating mechanism (an electric drive that changes air damper position).

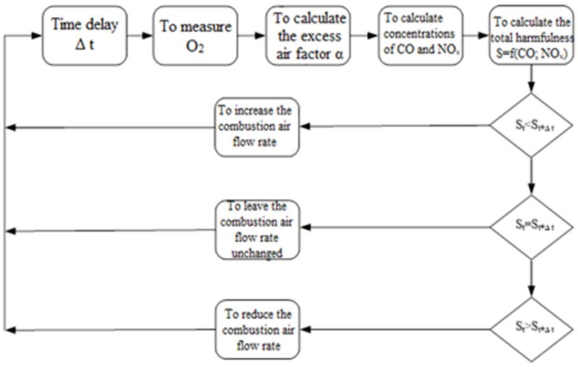

Fig.2 ACD operation algorithm

Arduino UNO controller was chosen as a PLC due to its low price and functionality. 28BYj-48 stepper motor with ULN2003 driver was used as an AM. A 10 kΩ potentiometer was chosen as a sensor that imitated a combustion product oxygen sensor (Fig.3).

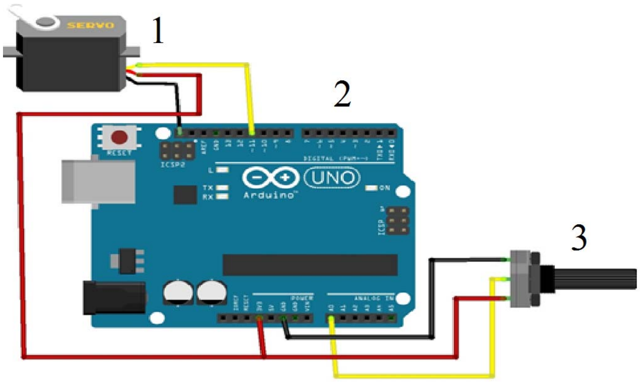

Fig. 3. ACS model diagram: 1 – stepper motor; 2 – controller; 3-potentiometer

Figure 4 shows listings of the sketch that realizes the algorithm, presented in Figure 2.

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```
#include "HardwareSerial.h"                    //
#include <Stepper.h>                           //
                                               //
const int steps=200;                           //
                                               //
Stepper myStepper(steps, 8, 9, 10, 11);        //объявляем мотор
                                               //
int value0;                                    //
int value1;                                    //
                                               //
void motor(float a, float b)                   //
{                                              //
  if(a > b)                                    //
  {                                            //если a больше b то
    Serial.println("право");                   //
    myStepper.step(steps);                     //движение на 20 шагов вправо
  }                                            //
  else if(a < b)                               //
  {                                            //если a больше b то
    Serial.println("лево");                    //
    myStepper.step(-steps);                    //движение на 20 шагов влево
  }                                            //
  else                                         //
  {                                            //
    Serial.println("STOP");                    //
    myStepper.step(0);                         //
  }                                            //
}                                              //
                                               //
float vred(float num)                          //
{                                              //вычисление по формулам
  float d = 21/(21-num);                       // d -> коэффициент избытка воздуха
  float y =-0.2424*pow(d,3)+0.8624*pow(d,2)-0.9939*d+0.3884;   // y -> вредность
  return y;                                    //
}                                              //
                                               //
void setup()                                   //
{                                              //
  Serial.begin(9600);                          //
  pinMode(A0,INPUT);                           //
  myStepper.setSpeed(60);                      //
}                                              //
                                               //
void loop()                                    //
{                                              //
  value0 = analogRead(A0);                     //
  Serial.println(vred(value0));                //
  delay(1000);                                 //
  value1 = analogRead(A0);                     //
  Serial.println(vred(value1));                //
  delay(1000);                                 //
  motor(vred(value0),vred(value1));            //
  delay(1000);                                 //
}                                              //
```

Fig.4. Listing of the sketch for the controller operation

Analysis of the program running with the use of a system monitor showed that the sketch had been written correctly. The sketch size is 2 KB.

III. CONCLUSIONS

1. The article proposes a method for conducting the experiment and mathematical processing of its results.
2. It proposes an ACS diagram and an algorithm that realizes the sequence of operations on minimizing harmfulness of boiler unit emissions on the principle of controlled incomplete combustion.
3. The algorithm may be used for ACSs that regulate air inlet to boiler units running on all types of fuel.
4. The article proposes a C++ program that realizes the presented algorithm.

REFERENCES

[1] Roslyakov, P.V. Controlled Incomplete Combustion as an Efficient Method to Reduce Nitrogen Oxide Emissions / P.V. Roslyakov, I.L. Ionkin, L.E. Egorova. – Available at: http://www.rosteplo.ru/Tech_stat/stat_shablon.php?id=2041, free access. Title from the screen. – In Russian (access date: 26.05.2019).

[2] Pleshanov, K.A. Developing and Studying a Method for Combustion of Fuels with Moderate Controlled Incomplete Combustion: abstract of the thesis for the degree of Candidate of Technical Sciences. / K.A. Pleshanov. – Moscow, 2010. – 15p.

[3] Kvyatkovskaya, I.Y., Kosmacheva, I.Y.,Kosmacheva, I., Sibikina, I., (…), Rudenko, M., Barabanova, E.A. Modular structure of data processing in automated system of risk management in the fisheries industry //Communications in Computer and Information Science. – vol. 754.-2017.-pp.284-301.

[4] Filinkov, L.I., Likhter A.M. Analysis of Approaches to Implementation of Decision Support System for Reducing Boiler-House Emissions into the Air. Caspian Journal No.3, 2019, p.11-17 (in Russian). DOI 10.21672/2074-1707.2019.47.3.010-017.

[5] Vytovtov, K.A., Tarasenko, Yu.S. The 2 x 2-matrix method for two-dimensional parametric system. Mathematical Methods in Electromagnetic Theory, MMET, Conference Proceedings 4581030, p.460-462. DOI: 10.1109/MMET.2008.4581030