Environment Protection Engineering

Vol. 42 2016 No. 1

DOI: 10.5277/epe160107

JANUSZ BUJAK[1], PIOTR SITARZ[1]

REDUCTION OF NO_x AND CO EMISSIONS THROUGH THE OPTIMIZATION OF INCINERATION PARAMETERS IN A ROTARY KILN

Theoretical and experimental results of the investigation illustrate how the rotary kiln operation affects the oxygen demand in the combustion of meat and bone wastes. The main objective of this study was to achieve optimal CO and NO_x emissions for the cyclic operation of a rotary kiln, including in stoppage/operation mode. The tests were carried out in a plant in Poland for thermal animal waste management. A rotary kiln with a maximum capacity of 1000 kg/h was used to incinerate bones, carcasses, processed meat and by-products. The results showed that excessive short-term (1 min) CO and NO_x emissions could be prevented by using appropriate time settings for the kiln rotation and adjusting the air flow to the afterburner chamber. Despite the strong negative correlation between CO and NO_x emissions, we found an operation level that met the strict requirements of the new EU Directive 2010/75/EU of the European Parliament and the November 24, 2010 Council on industrial emissions.

1. INTRODUCTION

Fossil fuel consumption contributes to the emissions of carbon dioxide (CO_2) and many other harmful compounds. To reduce this effect, researchers need to focus on improving the efficiency of both existing and new energy systems. Many methods exist for reducing energy and heat consumption by CO_2 and other pollutants [1–8]. However, new ways of producing thermal energy need to be developed. These new technologies should lead to solving issues with wastes and reduce fossil fuel use [2, 6]. The transformation of waste into thermal energy is considered to be an energy recycling process.

Waste management, i.e., the collection, transport, recovery, neutralization and supervision of actions and localities related to waste disposal, is one of the most significant

---

[1] PPM PROMONT Bydgoszcz, Jagiellońska 35, 85-097 Bydgoszcz, Poland, corresponding author J. Bujak, e-mail: dn@promont.com

fields in environmental engineering and protection. Waste utilization is increasingly important because of the growing amount of waste. This problem is a result of the minimal improvements in this area, and the rising number of complex obligations imposed on those who produce and manage waste. For instance, all incineration plants must comply with strict emission limits, such as those listed in EU-Directive 2000/76/EC (European Community, 2000) [9].

To satisfy these regulatory requirements, a plant exhaust gas cleaning system must be designed based on specific environmental characteristics of the plant [10]. A large number of harmful compounds are created in the combustion process, including dust, sulfur oxides (SO_x), nitrogen oxides (NO_x), hydrochloric acid (HCl), hydrofluoric acid (HF), dioxin, furans, and heavy metals. Most of these pollutants are removed by specific treatments such as neutralization for acid gases, filtration for fly ashes and absorption with activated carbon for dioxins [11] and other micropollutants such as metals [12]. Particulate matter emissions must be controlled using fabric filters because the efficiencies of electrostatic precipitators (which can reach 99.5–99.8%) [13] often do not satisfy the regulatory limits.

Carbon and nitrogen oxides are the most significant pollutants produced during the incineration processes. Current emission standards are difficult to meet for contemporary waste incineration systems (European Community, 2000). To minimise and control carbon monoxide (CO) and nitrogen oxides (NO_x) emissions, it is important to maintain an optimum ratio of excess air in the combustion chamber.

Kuo [14] developed a combustion control algorithm that plant operators could use to achieve stable combustion with various fuel parameters by regulating the air supply and fuel feed rate. The combustion control model was based on the mass and thermal energy balance of the incinerator. The fuel burning rate and its heating value had to be accurately determined to obtain realistic results from the simulation model. The optimum algorithm for combustion control was developed using excess oxygen (O_2), flame temperature and CO emission data [15]. Here, the reduction of the formation of pollutants such as CO and soot which result from fuel-rich combustion conditions in the rotary kiln has been discussed [16].

The objective of this study was to determine a range of time settings for the drum rotation (in the primary combustion chamber) and the air flow supply to the secondary chamber to lessen short-term (1 min) CO and NO emissions.

2. PROBLEM DEFINITION FOR NO_x AND CO EMISSIONS

Directive 2010/75/EU of the European Parliament and the November 24, 2010 Council on industrial emissions introduced stricter NO_x emission standards for energy installations. This directive specified a maximum concentration of emissions to be 200 mg/Nm^3 at 273 K, under the pressure of 1013 hPa, dry flue gas content of 3% O_2

for the gas and liquid fuels, 6% for solid fuels, and 11% for waste incineration. Some of the legal changes regarding waste incineration were anticipated. For example, it was expected that the target maximum NO_x concentration in flue gas would be lowered from the current standard of 200 mg/Nm^3 to 70 mg/Nm^3. However, the revised emission standards imposed stringent restrictions on CO emissions, including a daily limit of 50 mg/Nm^3 and 30 min averages of 150 mg/Nm^3 (for 100% of the measurements) and 100 mg/Nm^3 (for 97% of measurements). The 30 min average criteria for CO emissions are particularly difficult to maintain. Due to the requirements of 2010/75/EU, the combustion process must be stopped in the case of exceeding the daily or half-hourly emission limit values (concentrations) for polluting substances like NO_x and CO. Waste incineration kilns are exposed to high CO concentrations during the processes of loading waste with a bin tipper or operating the combustion chamber in a cyclical operation/stoppage mode. Furthermore, a strong negative correlation exists between CO and NO_x emissions. NO_x emissions decrease with increasing CO emissions and increase with decreasing CO emissions. These relationships make it difficult to comply with the applicable emission standards. Thus, the following emission reduction methods were applied in this study:

- a large volume afterburner chamber for CO,
- selective non-catalytic reduction (SNCR) by adding urea to the flue gases within the so-called temperature window for NO_x.

3. EXPERIMENTAL

3.1. INSTALLATION

The thermal system used for continuous (i.e., 24 h/day) waste treatment and heat recovery is shown in Figs. 1, 2. The system is composed of the following elements.

- A loading system which is a set of devices for preparing and loading wastes.
- A rotary kiln of the capacity of 1000 kg/h. It serves to incinerate bones, carcasses, processed meat and the remaining by products. The kiln is inclined at 2–4% towards the after-burner chamber, to incinerate animal by-products using additional fuel. The duration of the combustion process depends on the calorific value of waste and the humidity. The waste humidity should not exceed 70%. The density of the waste should remain within a 200–1000 kg/m^3 range. An external source of energy must be used to initiate incineration in the combustion chamber (at ca. 650 °C). Gaseous or liquid fuel-fired burners are used as energy sources.
- An afterburner chamber (a secondary combustion chamber) in which combustible gases produced in the combustion chamber are burned. The incineration proceeds at temperatures ranging from 850 °C to 900 °C for a minimum residence time of the burning gases of 2 s. The temperature range of 850–900 °C in the secondary chamber is maintained using

additional burners fed with natural gas NG-50 or heating oil. The temperature of the flue gases at the outlet may exceed 1000 °C for waste with a high calorific content.

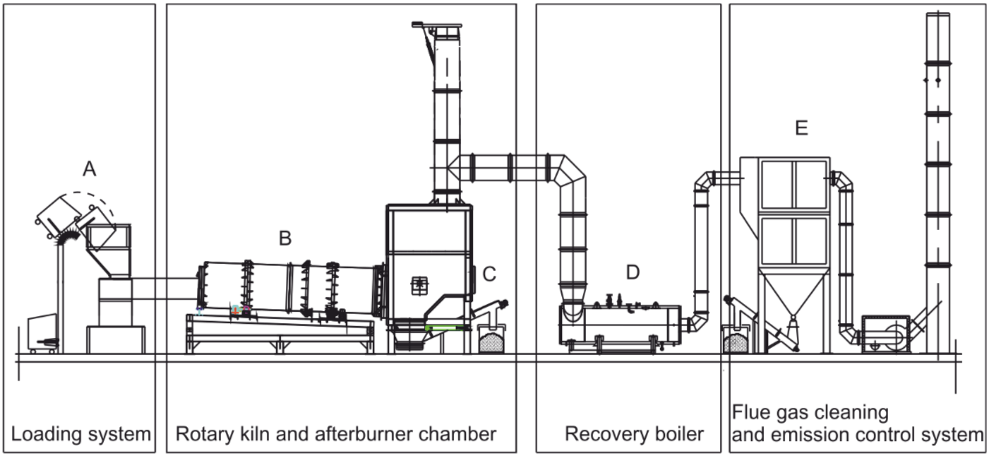

Fig. 1. Schematic of the system of waste utilization with heat recovery

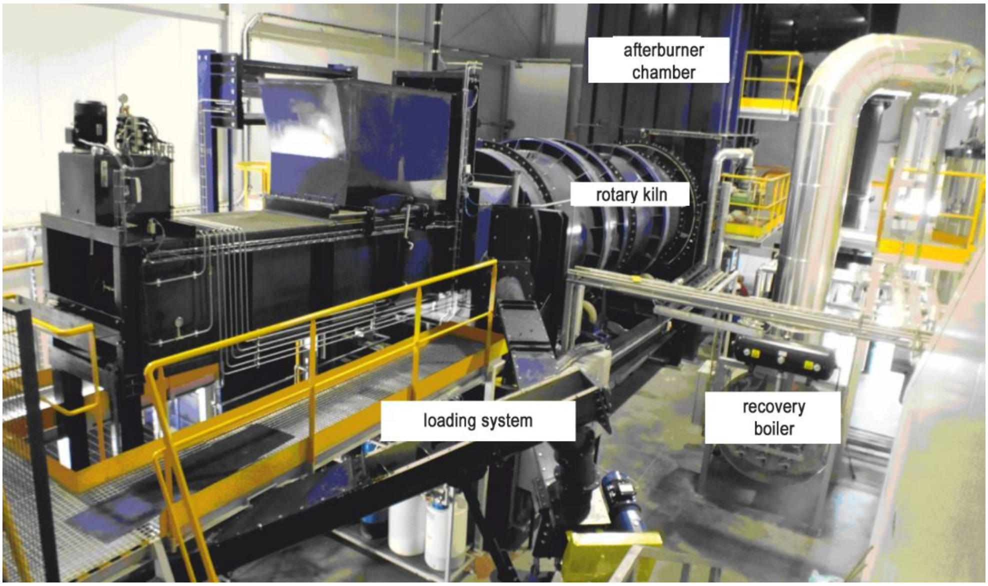

Fig. 2. Installation for thermal waste management

- A steam boiler (a recovery boiler) heated up by the flue gases leaving the afterburner chamber at 850–900 °C generates saturated steam. The temperature of the flue gases leaving the boiler fluctuates between 220 and 280 °C depending on the pressure of saturated steam and the boiler heat load.

- A flue gas cleaning and emission control system consisting of a bag filter for removing dust and a computer for emissions control.

The installation also includes urea and sorbent dosing systems. The SNCR system was stopped during test period to avoid influence of this factor to NO_x concentration. The injection point is located at flue gas pipe after discharge chamber. The sorbent dosing system does not affect the NO_x and CO concentrations in flue gas.

3.2. MEASUREMENT SYSTEM

The measurement system (Fig. 3) consists of the following components:

- a Vortex flowmeter measuring the mass flow rate of air used for burning fuel wastes in the combustion chamber with a 1.25% accuracy (AM1),
- a Vortex flowmeter measures the mass flow rate of the air used for the after-burning flue gases in the discharge chamber with a 1.25% accuracy (AM2),
- a computer for emissions control.

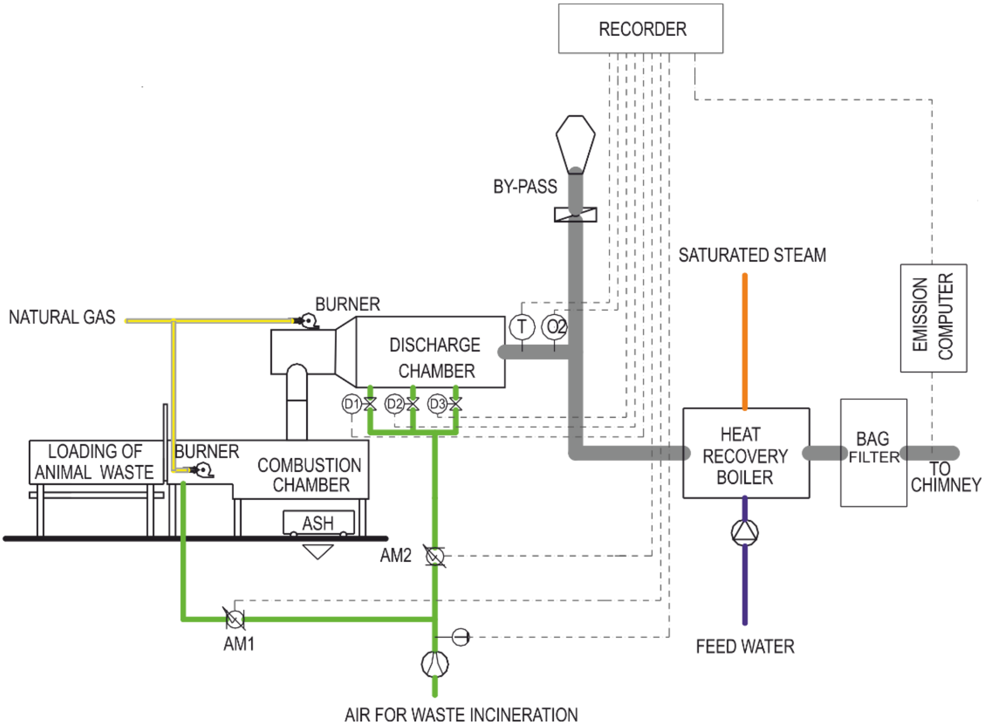

Fig. 3. Measurement system for the installation under study

The parameters monitored by the computer for emissions control are presented in Table 1.

Table 1

Flue gas parameters measured by the continuous control system, measurement ranges and errors

Measured value	Measurement range	Measurement error
Gas humidity, H_2O	0–30 vol. %	2%
Sulfur dioxide, CO_2	0–2000 mg/Nm^3	
Nitric oxides, NO_x	0–2000 mg/Nm^3	
Carbon monoxide,	0–700 mg/Nm^3	
Carbon dioxide, CO_2	0–20 vol. %	
Hydrogen chloride, HCl	0–50 mg/Nm^3	
Hydrogen fluoride, HF	0–10 mg/Nm^3	
Oxygen, O_2	0–25 vol. %	
TOC	0–100 ppm 0–160 mg/Nm^3	1%
Dust content	0–10 mg/Nm^3	2%
Gas flow, V	0–5000 Nm^3/h	
Gas temperature, T	0–2000 °C	
Gas static pressure, P_{stat}	0–1600 hPa	0.25%

4. RESULTS OF MEASUREMENTS

4.1. PERIODIC DROP IN FLUE GAS EXCESS OXYGEN CONCENTRATION IN THE SECONDARY CHAMBER

The operation cycle of the incinerator includes rotation and stoppage stages. The duration of every stage depends on the conditions of the actual incineration process and the physiochemical properties of the incinerated waste. During the rotation stage, the outer layer of the incinerated waste slips towards the secondary chamber, exposing a new layer of unburned waste. During the stoppage stage, the newly exposed layer undergoes steady incineration to form a slag.

The incineration process is intensified by rotating the kiln which temporarily decreases the excess O_2 concentration in both chambers. Oxygen deficiency occurs after the rotation begins and persists for approximately 100 s (Fig. 4). To compensate for the decrease of O_2 contents in the flue gases, air is introduced from the D1, D2 and D3 valves (Fig. 3). An excessive air flow can result in overregulation of O_2 in the flue gases (Fig. 4).

In the study, a decrease in the excess air in flue gases occurred approximately 25 s after the beginning of the rotation stage, causing a rapid compensation in the O_2 deficiency. The valves supplying the air to the secondary chamber were opened. Operation under these rapidly changing conditions produced significant short-term peaks in the carbon monoxide (CO) and nitric oxides (NO_x) emissions. The data shows that the carbon oxide emissions rapidly increase with decreasing O_2 concentrations in the flue gas. Insufficient excess air in flue gases in the primary and secondary chambers results in incomplete combustion. Although the valves that adjust the air flow to the afterburner chamber open after the excess oxygen in the flue gases decreases, the combustion process of the newly exposed outer layer occurs so rapidly that a short-term peak in the carbon oxide emissions in the flue gases is very likely to occur.

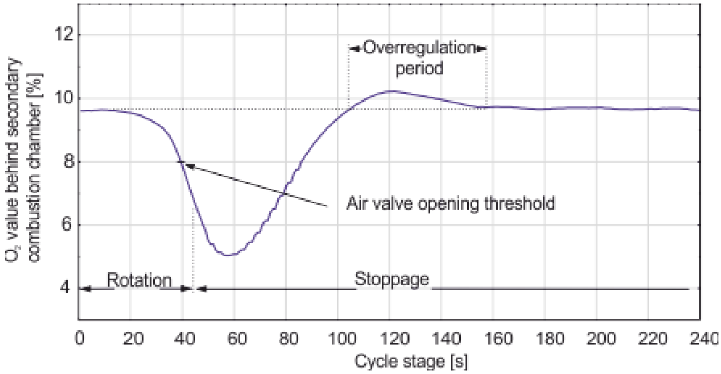

Fig. 4. Decrease and overregulation of O_2 in the flue gases
for one operation cycle of the rotary kiln

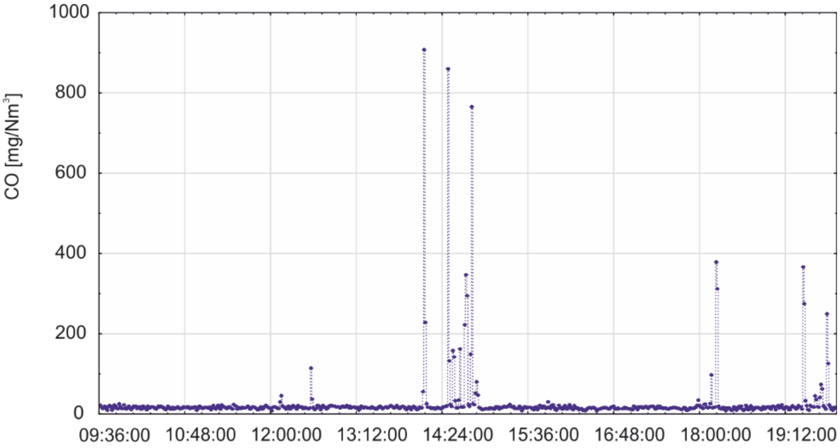

Fig. 5. Cases of exceeded CO limit value during the operation of the installation

Figure 5 provides an example of peaks of concentration of carbon oxide during the operation period. The actual concentrations were recalculated for 273 K, 1.013 hPa, 11% O_2 and 0% H_2O. When a few peaks in the CO concentrations occur at approximately 900 mg/Nm^3, the calculated 30 min average concentrations can exceed the regulated levels allowed by the Directive 2010/75/EU. If appropriate pollutant levels are not maintained, the waste utilisation process may be temporarily suspended or the installation may be shut down.

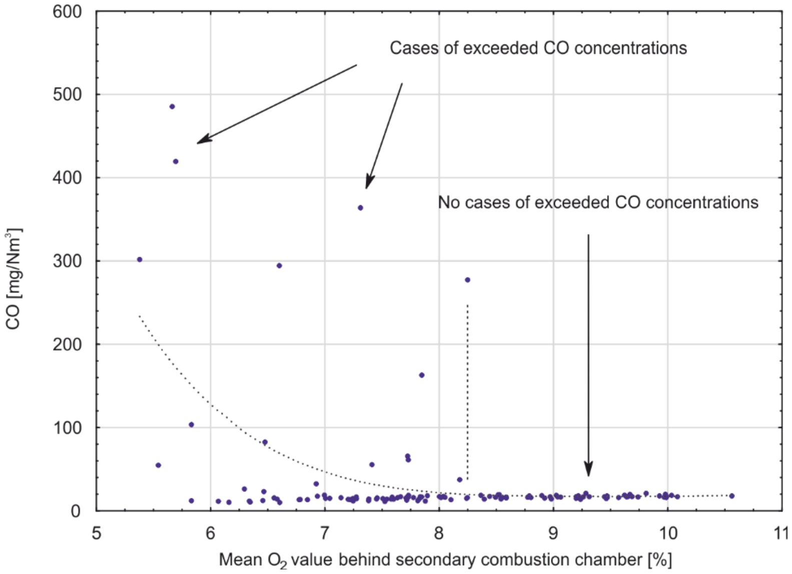

Fig. 6. The increased number of cases in which the limit value of CO concentration was exceeded

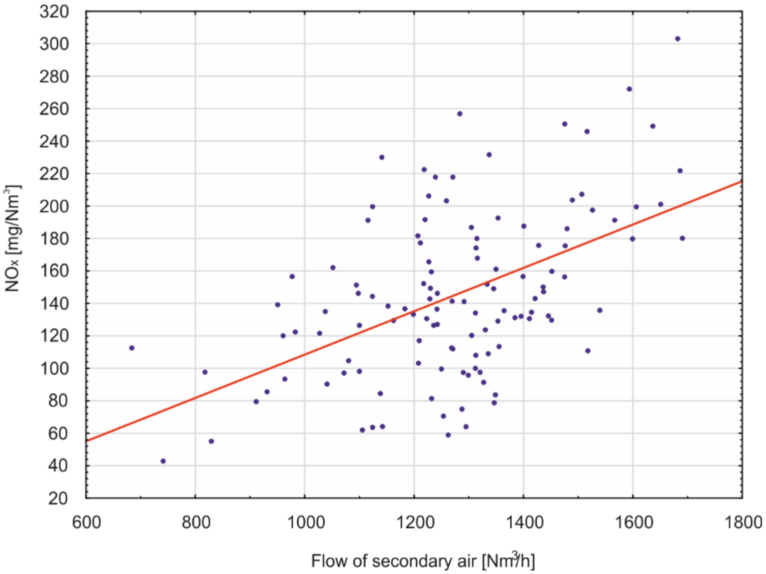

Fig. 7. Relationship between the NO_x concentration and the flow of secondary air. The SNCR system was stopped during test period

The recorded average CO concentrations behind the secondary combustion chamber in dependence of the average O_2 contents are shown in Fig. 6. The data were recorded when the open and close control was switched to automatic for the three valves which supplied the air to the afterburner chamber. The number of cases of limit CO concentrations increases as the average O_2 content decreases. However, for the cycles in which the O_2 content in the flue gases exceeded 8.2% on average, the cases in which the CO concentration increased did not exceed the limit 30 min values.

The empirical data showed that the NO_x concentration increased as the air flow was supplied to the secondary chamber (Fig. 7). The strength of the observed correlation in Fig. 7 decreased because of the addition of urea to the flue gas within the temperature window (using the SNCR secondary method).

The system under study contains three air valves, D1, D2 and D3 (see Fig. 3). These air valves open when the O_2 concentration in the flue gas decreases below the individually set thresholds. The valves are closed again in sequence when the O_2 content increases. The valves can be completely opened or closed within 30 to 150 s.

4.2. UNCERTAINTY MEASUREMENTS

The calculated mean and extended measurement uncertainties are given in Table 2.

Table 2

Measurement uncertainties of the CO, NO_x and O_2 flow of secondary air

Standard measurement uncertainty for CO, mg/Nm^3	24.5±0.49
Extended measurement uncertainty for CO, mg/Nm^3	24.5±1.47
Standard measurement uncertainty for NO_x, mg/Nm^3	114.9±2.30
Extended measurement uncertainty for NO_x, mg/Nm^3	114.9±6.90
Standard measurement uncertainty for O_2, %	9.2±0.18
Extended measurement uncertainty for O_2, %	9.2±0.55
Standard measurement uncertainty for air flow, Nm^3/h	1532.6±19.15
Extended measurement uncertainty for air flow, Nm^3/h	1532.6±57.47

5. DESIGN OF EXPERIMENT

5.1. PURPOSE AND ASSUMPTIONS

The objective of the tests was to select a range of time settings in the rotary kiln (combustion chamber) and the air flow supplied to the secondary chamber. The optimal oxygen concentration in the afterburner chamber must be maintained within this range of time settings. This optimal value results in a trade-off between the CO and NO_x emissions despite periodical disruptions in the combustion process from the chamber rotation.

We also investigated whether limiting significant drops in the excess O_2 in both chambers decreased the probability of exceeding the limit CO concentrations. At the same time, limiting significant decrease in the excess oxygen content in the flue gases significantly decreases the possibility of undue increases (overregulation) in the excess O_2 and associated increased in the NO_x concentration in the flue gases.

In this study, the schedule shown in Table 3 was followed. The following parameters were investigated for their potential effects on the intense decrease in the O_2 and the occurrence of limit short time CO and NO emissions:

- the rotation time of the primary chamber,
- the air flow supplied to the secondary chamber through the D1, D2 and D3 valves.

The rotation time (the drum rotation speed at the plant under study was constant) promotes the intensification of combustion and decreases the excessive O_2 content in both chambers. Three rotation times were investigated in the study: 30, 50 and 70 s.

Additional air can be supplied to the combustion chamber by three individually controlled valves. The air flow increases the O_2 content in the afterburner chamber. The air flow in the secondary chamber is automatically controlled by a sensor located behind this chamber and is based on the O_2 content in the flue gas. The automatic control mode of the air flow to the afterburner chamber was switched off. Our study schedule included three configurations for the valve (D1, D2 and D3) operation:

- only one valve open, D1,
- two valves open, D1 and D2,
- three valves open, D1, D2, D3.

The airflow rates at the three levels were measured with a flow meter AM2 and recorded with a measuring transducer (Fig. 3).

Table 3

Experimental plan

Rotation time [s]	Number of opened valves secondary air
30	1
50	
70	
30	2
50	
70	
30	3
50	
70	

5.2. RESULTS

The experiments were carried out twice in two independent series (Table 4). The following parameters were recorded during the tests:

- the flow of secondary air supplied to the afterburner chamber,
- the excess O_2 in the flue gases behind the afterburner chamber (at a frequency of 1 s).

The average excess air O_2 concentrations in the flue gases after the secondary chamber were measured in the tests. The secondary air flow was incrementally changed during the experiments by opening one, two, three air valves.

Table 4 shows the excess air (O_2) distribution in the flue gases behind the afterburner chamber after all of the intended experimental variables were introduced.

Table 4

Mean value of the excess air (O_2) in the flue gases behind the afterburner chamber

Primary chamber rotation time [s]	Number of opened air valves	Average air flow to the combustion chamber [m^3/h]	Average O_2 behind the afterburner chamber [%]
30	1	913	6.8
50		931	6.9
70		1090	4.4
30	2	1588	10.6
50		1584	8.9
70		1585	8.7
30	3	2148	9.5
50		2149	7.2
70		2159	8.5
30	1	921	9.8
50		902	8.0
70		1181	4.1
30	2	1581	9.2
50		1583	8.4
70		1709	8.1
30	3	2154	9.4
50		2148	8.3
70		2147	10.6

A preliminary analysis showed that setting long rotation time (70 s) at a low secondary air flow (D1) produced the lowest (ca. 4%) excess air O_2 concentrations behind the afterburner chamber. In this case, a large amount of waste remained unburnt because the relatively long rotation period in the primary chamber produced a high oxygen demand. The low flow of secondary air maintained throughout this cycle also resulted in a low oxygen concentration in the flue gases.

Analysing the results for other investigated combinations of settings showed that shortening the rotation time and extending the number of open air valves also limited the decrease in the O_2 concentration in the flue gases.

5.3. REGRESSION ANALYSIS

The regression function was estimated by replacing the number of opened air valves supplying air to the secondary chamber with the actual air flow supplied to the chamber (Table 4). A linear model with two-factor interactions Eq. (1) was used for the regression analysis:

$$y = a + bx_1 + cx_2 + dx_1x_2 \quad (1)$$

where: y – the average excess O_2 concentration in the flue gases behind the afterburner chamber, x_1 – the air flow supplied to the afterburner chamber, x_2 – the rotation time of the combustion chamber. The calculations were used to determine the values of the parameters in the model given in Eq. (1). These values are used in the function given in Eq. (2) which is plotted in Fig. 8.

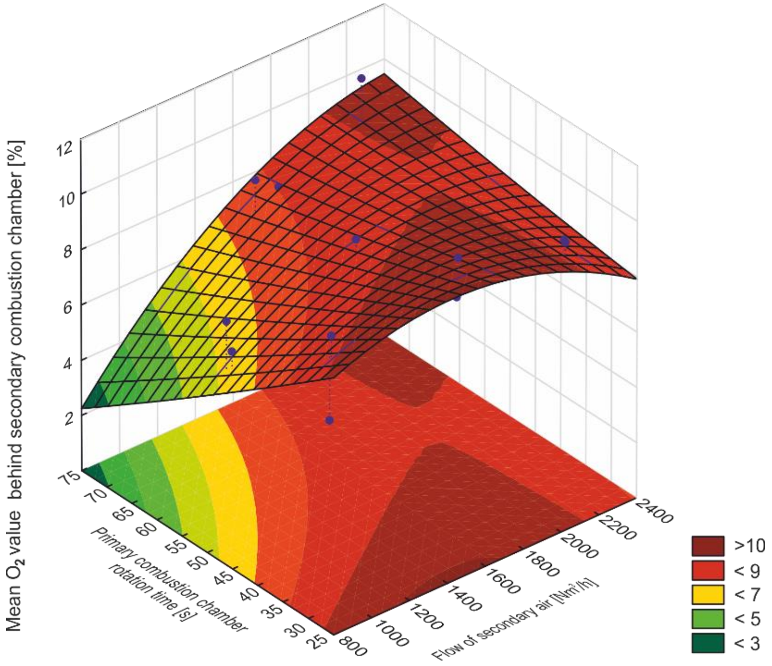

Fig. 8. Regression function of the excess air (O_2) concentration in the flue gases behind the afterburner chamber

The function using the determined parameters is given by:

$$y = 15.06 - 0.0027x_1 - 0.203x_2 + 0.0001x_1x_2 \tag{2}$$

for which the following characteristics were found:

- The standard deviation of the residual component (S_e) (the mean estimation error) was 1.288% of the O_2 concentration; the chance variation coefficient (V_e) was 0.16.
- The coefficient of determination R^2 was 0.58.
- The level of significance obtained from the *F*-statistics test was 0.005395 which was less than the assumed level of 0.05. Therefore, the null hypothesis that there was no statistical relationship between the variables used to formulate the model and the dependent variable was rejected.

5.4. DETERMINING THE OPTIMAL RANGE OF SETTINGS FOR THE OPERATING PARAMETERS OF THE INSTALLATION

The experimental studies presented in section 4.1 were used to determine optimal O_2 level in the flue gases below which the probability of occurring CO concentrations peaks dramatically increases (Fig. 6). On the other hand high level of O_2 is not a solution due to positive correlation between oxygen concentration and NO_x concentration (Fig. 7).

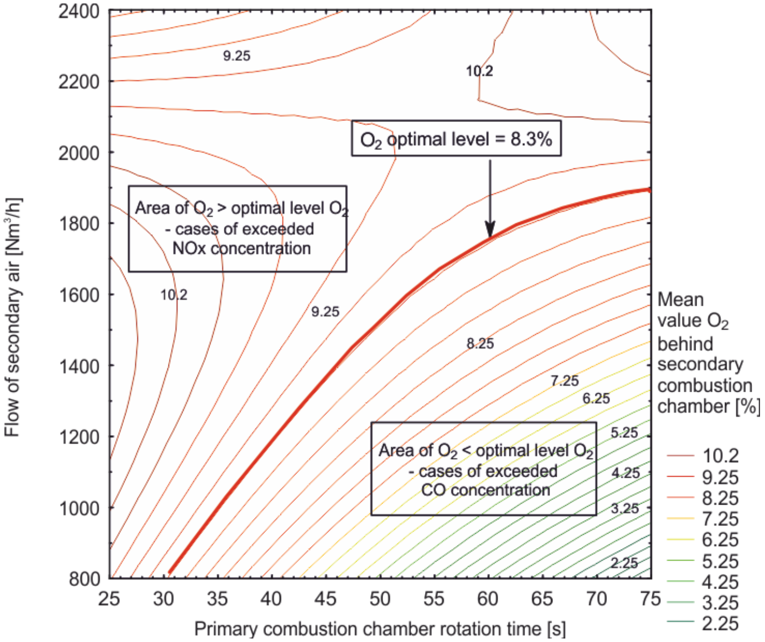

Fig. 9. Layer diagram used to determine the optimal oxygen content in the flue gases

Figure 9 shows the dependences of the secondary air flow volume on the chamber rotation time (Eq. (2) was used to predict the decrease in the excess O_2 content for each combination of parameters. There is also shown a distinct level line for the optimal O_2 content of 8.2%. It represents the set of optimal settings for this process to produce a trade-off between the CO and NO_x emissions.

Analysis of the installation operation showed that the combustion chamber rotation time was the most frequently varied control parameter. Thus, it was important to adjust the air flow to the altered rotation time of the secondary chamber to attain the optimal O_2 content of 8.2%.

Equation 2 has been transformed to calculate the air flow in function of the drum rotation time:

$$y = \frac{[\mathrm{O}_2] - 15.06 - 0.203x}{0.0027 + 0.0001x} \tag{3}$$

where: y denotes the air flow supplied to the afterburner chamber, Nm^3/h, x denotes the combustion chamber rotation time, s, and $[O_2]$ denotes the optimal O_2 concentration, %.

Application of Eq. (3) helps to prevent a sharp fall in the excess oxygen content in the flue gases during the rotation of the combustion chamber. Predicting the air flow volume prevented short-term carbon monoxide (CO) and nitric oxides (NO_x) emissions, which could not be eliminated by the current standard control systems. An additional feeding duct for air to the secondary chamber should be installed, and the chamber should be equipped with a flow meter and a control valve to regulate the opening level. The air flow supplied through this duct can be determined from Eq. (3). The additional air duct will act as a basic control system. Thus, in view of other random factors such as variable chemical composition of the exposed waste, handling of the operating system or deslagging, the existing cascade system of the three valves (D1, D2, D3) should be maintained as a supportive control.

6. CONCLUSION

Theoretical analysis and empirical studies were performed to determine the range of rotation time settings for a rotary kiln (the primary combustion chamber) and the volume of the supplied air flow to diminish short-term (1 min) carbon monoxide (CO) and nitrogen oxides (NO_x) emissions.

The pre-set parameter combinations associated with CO emissions, the combustion chamber drum rotation time and the secondary air flow can be determined in order that the mean O_2 content in flue gas will not decrease below the minimum limit level. This method was used to determine the installation operation parameters to avoid the peaks of CO concentration in the flue gases.

The pre-set combinations associated with the NO_x emissions were determined by noting the observed positive correlation between the secondary air flow and the NO_x concentrations in the flue gases, showing that the air supplied to the afterburner chamber should be minimised. However, the air flow should not be smaller than the optimal air concentration in the flue gases.

The research method and experimental planning presented in this paper can be applied to all waste incineration systems, and to rotary kilns in particular. A specific equation to calculate operation parameters (for the mean flow of secondary air) in advance can be determined for various waste types. Various types of incinerated waste require different formulas, which can be stored in memory of programmable logic controller (PLC). The operator of the installation would then introduce the type of waste to be burnt and the PLC controller algorithm would automatically select the appropriate formula and proper pair of settings for rotation time and air flow.

REFERENCES

[1] BUJAK J., *Energy savings and heat efficiency in the paper industry. A case study of a corrugated board machine*, Energy, 2008, 33, 1597.

[2] BUJAK J., *Mathematical modelling of a steam boiler room to research thermal efficiency*, Energy, 2008, 33, 1779.

[3] BUJAK J., *Minimizing energy losses in steam systems for potato starch production*, J. Clean. Prod., 2009, 17, 1453.

[4] BUJAK J., *Experimental study of the energy efficiency of an incinerator for medical waste*, Appl. Energy, 2009, 86, 2386.

[5] DOVÌ V.G., FRIEDLER F., HUISINGH D., KLEMEŠ J.J., *Cleaner energy for sustainable future*, J. Clean. Prod., 2009, 17, 889.

[6] CONSONNI S., GIUGLIANO M., GROSSO M., *Alternative strategies for energy recovery from municipal solid waste: Part A: Mass and energy balances*, Waste Manage., 2005, 25, 123.

[7] KENDALL A., CHANG B., *Estimating life cycle greenhouse gas emissions from corn–ethanol: a critical review of current US practices*, J. Clean. Prod., 2009, 17, 1175.

[8] SARDIANOU E., *Barriers to industrial energy efficiency investments in Greece*, J. Clean. Prod., 2008, 16, 1416.

[9] European Commission, Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste. Official Journal of the European Communities, 2000, 91.

[10] POGGIO A., *Analisi energetica di impianti per la termoutilizzazione di rifiuti urbani*, 4 Convegno Nazionale Utilizzazione Termica dei Rifiuti. Associazione Termotecnica Italiana, Milan 2003.

[11] EBENER B., CLAYTON M., *Operating experience with filter bags in flue gas cleaning on refuse incinerators*, Filt. Sep., 1995, 32, 27.

[12] SEDMAN C.B., Controlling emissions from fuel and waste combustion, Chem. Eng., 1999, 106, 82.

[13] DEAN A., [in:] J.R. McDonald, A.H. Dean (Eds.), *Electrostatic recipitator manual*, Noyes, Park Ridge 1982, 484.

[14] KUO J.T., *System simulation and control of batch-fed solid waste incinerators*, J. Dyn. Sys. Measure. Con., 1996, 118, 620.
[15] GOOD J., NUSSBAUMER T., *Efficiency improvement and emission reduction by advanced combustion control technique (ACCT) with CO/lambda control and setpoint optimization, in: Biomass for energy and industry*. 10th European Conference and Technology Exhibition, Würzburg 1998, 1362–1365.
[16] NOLTE M., EBERHARD M., KOLB T., SEIFERT H., *Incineration optimization*, Chem. Eng., 2007, 793, 43.