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THE OPTIMIZATION AND DIAGNOSTICS OF COMBUSTION PROCESS WITH NUMERICAL MODELLING APPLICATION

OPTYMALIZACJA I DIAGNOSTYKA PROCESU SPALANIA Z WYKORZYSTANIEM MODELOWANIA NUMERYCZNEGO

The progressing development of industry and the associated rising environmental pollution create the need for the intensification of combustion processes and the implementation of increasingly stringent environmental protection standards. Therefore, an intensive progress in scientific and research work that is lately observed and studies with the use of numerical methods, are becoming an indispensable element of experimental research. This allows for: optimization of combustion processes, development of new designs of burners and technologies of low-emission combustion, as well as prediction of ecological effects. This article presents the possibilities of numerical modelling in combustion processes in heat furnaces. The chemistry of the combustion process was modelled in CHEMKIN software, while the dynamics of flue gas flow in the combustion chamber was modelled with the use of FLUENT software. Numerical computations were performed for both, the experimental chamber and the real objects, i.e. a pusher furnace and a sheet hardening furnace. The results of obtained measurements and numerical calculations clearly show that the use of hot air affects the growth of emissions, in particular NO_x. Furthermore, it has also been proved that the design and the appropriate location of the lance supplying the secondary air result in the reduction of emissions of nitrogen oxides.

Keywords: combustion, optimization, diagnostics, numerical modelling

Postępujący rozwój przemysłu i związany z tym wzrost zanieczyszczenia środowiska stwarza potrzebę intensyfikacji procesów spalania oraz wprowadzenia coraz to bardziej rygorystycznych norm ochrony środowiska. W związku z tym w ostatnim czasie obserwuje się intensywny postęp w pracach naukowo-badawczych, a badania z wykorzystaniem metod numerycznych stają się nieodzownym elementem badań eksperymentalnych. Umożliwia to optymalizację procesów spalania przy jednoczesnym oszacowaniu efektów ekologicznych, a w rezultacie rozwój nowych konstrukcji palników i specjalnych, niskoemisyjnych technologii spalania. W artykule przedstawiono możliwości modelowania numerycznego procesów spalania i dynamiki gazów w piecach grzewczych. Chemię procesu spalania zamodelowano przy wykorzystaniu oprogramowania CHEMKIN, natomiast dynamikę przepływu spalin w komorze spalania programem FLUENT. Obliczenia numeryczne przeprowadzono zarówno dla komory eksperymentalnej, jak i dla rzeczywistych obiektów, a mianowicie pieca przepychowego i pieca do hartowania blach. Wyniki uzyskanych badań pomiarów i obliczeń numerycznych jednoznacznie wskazują, że zastosowanie gorącego powietrza wpływa na wzrost emisji zanieczyszczeń, a w szczególności NO_x. Ponadto udowodniono, że na obniżenie emisji tlenków azotu ma wpływ konstrukcja i odpowiednie umiejscowienie lancy doprowadzającej powietrze wtórne.

List of designations

A – coefficient describing the reaction rate, $m^3/(mol \cdot s)$,
E – activation energy, kJ/mol,
T – temperature, K,
R_u – universal gas constant, $8.315 \cdot 10^{-3}$ kJ/(mol·K),
k – equilibrium constant values,
λ – excess air ratio,
l – length, m,
d – diameter, m
$\dot{m}$ – inlet mass flow, kg/s

1. Introduction

Diagnostics and optimization of combustion processes are a diverse, constantly evolving field of science, without which the improvement of design and technology of heating equipments would be impossible. An important issue of diagnostics of combustion processes is the identification of chemical composition of the combustion products with simultaneous

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minimization and reduction of pollutant emissions, as well as the improvement of the process efficiency. Appropriate diagnostics and optimization of industrial processes, in particular the combustion, affects both the economical and the ecological security of the whole process. Early detection and location of defects allow to avoid serious risks, as well as environmental and related to the weak points of the equipment and installation, which fixing would be very expensive. The more complex process, the greater probability of irregularities during the cycle of technological processes [14, 15].

In the high-temperature heat furnaces, primarily natural gas-fired, nitrogen oxides and carbon monoxide are considered to be serious pollutants [1].

Proper control and monitoring of environmentally harmful combustion products can be provided by modern diagnostic methods and computer support in the form of professional computational tools [15]. The literature of this issue mentions combustion modelling as an essential and indispensable element of optimization in industrial boilers and furnaces. Due to many problems occur during the analysis of combustion processes (turbulent nature of combustion, discrepancies in reaction rate constants and energy activation, the imperfections of the existing calculation methods, simplifications in the calculation models) so more accurate calculation methods are required. Above mentioned problems, such as complex kinetics of chemical reactions, being a basis for analysis of high-temperature oxidation processes, should be taken into account [1].

Among many of the most widely used commercial softwares used in modelling of combustion process, the Chemkin software is listed as one of the most common. This software is a basis for analysis of the mechanism of formation and reduction of harmful substances in the combustion chambers [27].

In this paper, the analysis of the chemical composition of flue gas from laboratory chamber and heat furnace, with the use of above mentioned software, were performed.

2. Influence of combustion process parameters on nitrogen oxides emission

In practice, the combustion process is monitored and controlled by several major parameters, such as: excess air and air gradation, fuel properties (chemical composition and physical parameters), temperature, method of heat removal, the content of oxygen in oxidant, outflow velocity and residence time, degree of stream turbulence, the type of flame, etc. [30, 31]. The influence of these parameters on combustion process has been described in many works [11, 12, 13, 24, 29, 33].

Considering the possibility of fuels combustion, one of the basic and required condition that must be fulfilled, is the simultaneously supply of necessary amount of oxygen into combustion chamber in order to produce a combustible mixture corresponding at least to stoichiometric composition [21].

Combustion of fuels is the main source of energy production (85÷95%) in Poland and worldwide. But it is also the main source of anthropogenic emission of pollutants. About 75÷85% emission of NO_x and SO_2, 55÷75% of CO, 55÷80% of particular matter and 95% of CO_2 is a result of fuel combustion. In these processes more than 70 harmful substances or groups of substances are produced. Therefore, the fuels combustion should be optimized simultaneously with energy and environmental criteria. The energy criterion requires keeping the assumed technological parameters (efficiency, temperature, pressure in the chamber, the composition of products, thermal emissivity, and others) at the level of possible highest energy efficiency. Ecological criterion leads to the minimization of harmful substances emissions. The classification of harmful substances can be made with the use of various criteria [30, 31].

Excess air ratio plays a key role in methods of combustion with air and fuel gradation. This is particularly concerned to the mechanism of fuel NO_x emissions. Generally, it is assumed that, in each case of combustion of lean mixture ($\lambda > 1$) the total excess air ratio should be slightly higher than unity. Limitation is the danger of excessive chemical loss of combustion. In operating practices, reduction of total λ significantly reduces emissions of NO_x [30]. Studies of Jun X. et al. [12] suggest that initially NO_x emissions increase, and then slowly decrease with the rise of excess air ratio. An important parameter affecting the NO_x emission is the temperature in the combustion zone. Fuel nitrogen oxides weakly depend on temperature. However, the general NO_x emission clearly increase as a function of temperature, when the thermal oxides are dominant. The rising temperature of the reduction zone, during gradual combustion with primary excess air ratio of λ_1 = 0,5-0,9, affect the increase of the reaction efficiency of NO reduction, results in lower vent emission. A similar effect concerns the turbulence intensity and residence time in the reduction zone. The increase in these both parameters in the reduction zone fosters minimizing the NO_x vent emission, contrary to the over-stoichiometric combustion. The reduction of NO_x emission is also influenced by the turbulence intensity. The greater the turbulence, the higher production of nitrogen oxides is in the single-step, over-stoichiometric combustion. In order to reduce the nitrogen oxides formation the following parameters should be minimized: the flame kernel temperature, the oxygen content in the combustion zone, and the residence time in the high temperatures zone [30, 31, 32].

Reduction of gaseous emissions is absolutely necessary and arises from the constant intensification of combustion processes and the implementation of increasingly stringent environmental standards. It forces the progress of research in developing new designs of burners and special burning techniques allowing for reduction of nitrogen oxides emission. The methods of NO_x emission reduction are divided into two main groups, i.e. primary and secondary.

Jun X. et al. [12] in their own studies have shown that NO_x emission depends also on the used fuel type, namely content of nitrogen. In industrial furnaces the favourabl conditions for the nitrogen oxides formation appear. This is primarily due to the high temperature of the combustion process. Thus, special attention is given to decrease the maximum flame temperature. Among the most commonly used methods of its reduction primarily should be enumerated [22]: construction of new types of burners for eliminating temperature maxima in the flame burners, such as GAFT burners, flue gas recirculation, protracted combustion, consisting in the gradation of air and fuel injection, water injection into the combustion chamber, reduction of air heating, reduction of the heat loss of the combustion chamber. Many works have devoted attention to the issue of nitrogen oxide emissions reduction [4, 16, 19, 23, 24, 25, 28, 34, 36], and the results of these studies are the basis for further development of these methods.

The Department of Industrial Furnaces and Environmental Protection also conducts experiments aimed at low-emission fuels combustion.

3. Numerical modelling

Nowadays, numerical methods have found a wide range of applications in many fields of science and have became an indispensable element of experimental research. Since more than ten years studies on a large scale in numerous scientific centres abroad have been conducted. In Poland, for a few years, research on the numerical modelling of combustion processes and reduction of pollutants emission have been also carried out [3, 7, 8, 17, 20, 26]. Numerical simulations enable a relatively simple optimization of the heating equipments operation and partial elimination of expensive experimental studies. Softwares for the numerical analysis of the above mentioned processes have wide possibilities of application and its increasing popularity appears in many fields of science and economy. Numerical modelling plays a particularly important role wherever the implementation of modern methods, aimed at the optimization of production processes, involves high financial outlays. It is also very useful when the evaluation of conceivable effects under industrial conditions is impossible due to the complexity of problems related to combustion processes and fluid dynamics of flue gas flow [2, 5].

During the numerical modelling of the chemistry of combustion processes different types of chemical mechanisms and models were used [6, 18]. The most widespread and common is the Miller-Bowman mechanism (M-B). During numerical computation, it is important to base on the one chosen mechanism in order to avoid discrepancies in the values of reaction rate constants, which were taken from the literature sources. Beyond the commonly known the Miller-Bowman mechanism [18], there are also other mechanisms, such as Burcat, Konnov, and many others. That large number of models differs not only in number of used reactions, compounds and chemical elements, but also in the values of reaction rate constants. It is a well-know fact that not all reactions are equally important. Depending on the conditions under which the methane oxidation process runs, i.e. pressure, temperature, as well as the quantity and composition of the oxidizer, some reactions are dominant, while the others can be omitted, due to their influence on the process is insignificant. The number of reactions in these models reaches almost 2000 with 250 compounds, while the basic model for the methane combustion can be described by 6 components, i.e. CH_4, CO, O_2, H_2O, CO_2 and N_2. The number of components required for reduction of NO concentration in this model equals nine (CH_3, CH_2, CH, H_2, H, OH, O, HCN, HCNO). According to the analyzed problem, the basic model of methane combustion can be extended by other compounds and reactions, based on the existing mechanisms, in particular the M-B mechanism [2, 6, 7, 8, 20].

Recently, the issue of numerical modelling of chemistry of combustion process has become very popular subject. Therefore, many new mechanisms, based on existing models, were created. The values of kinetic constants in these models have been determined experimentally by the researchers.

CHEMKIN is one of the most successful and enduring products to come out of Sandia National Laboratories. It is used in the combustion, microelectronics, power engineering and chemical processing industries. Reaction Design offers multiple CHEMKIN products to satisfy unique requirements. CHEMKIN-PRO is specifically designed for large chemical simulation applications requiring complex mechanisms. The CHEMKIN software is able to examine thousands of reaction combinations to develop a comprehensive understanding of a particular process, which might involve multiple chemical species, concentration ranges, and gas temperatures. Designers of gas turbine, boiler and piston engine strive for fulfilling low-emissions regulations as well as for improvement the efficiency of fuels combustion process. Effective simulation of the complex combustion chemistry is required in order to design the cost-effective systems with reduced pollutant emissions [9, 10].

The application of CHEMKIN and FLUENT allows to model both, the chemical composition of combustion products during natural gas and biofuels co-combustion, and methods of NO_x reduction. The optimum number of reactions and chemical compounds were selected based on the review of relevant literature and the results of performed modelling research. In the modelling procedure existing reaction mechanisms and studies, carried out in the field of this subject with application of CHEMKIN-PRO software, were used.

4. Research

Presented in this paper studies include both, the laboratory experiment, as well as numerical calculations with the use of Fluent and Chemkin software. The aim of the study was as follow:

- diagnostics of natural gas combustion in terms of pollutants emission, in particular CO and NO_x,
- optimization of combustion process by appropriate modification of the process organization (air staging),
- visualization of the combustion process.

4.1. Laboratory studies

The aim of this study was to determine the reduction effectiveness of the pollutants formed during the combustion with air staging. Particular emphasis was put on proper selection the appropriate location and method of secondary air flow supply, as well as on determination the shape of the flame. Temperatures in the combustion chamber, the concentration of pollutants (NO_x and CO) in flue gas were measured, as well as a visualization of the flame shape was performed. Measurements were made in two versions, during:

- air staging with the injection of secondary air into the chamber, parallel to the axis of the flame,
- air staging with the injection of secondary air perpendicular to the axis of the flame.

Diagram of the experimental stand is presented in Fig. 1 and the general view in Fig. 2.

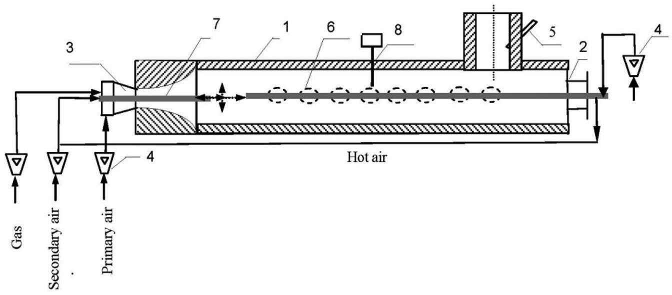


Fig. 1. The scheme of the experimental stand: where: 1 – chamber, 2 – sight-glass, 3 – burner, 4 – rotameters, 5 – TESTO 350 analyzer, 6 – measuring holes, 7 – secondary air lance, 8 – sensors with computer card DaqLab/2000

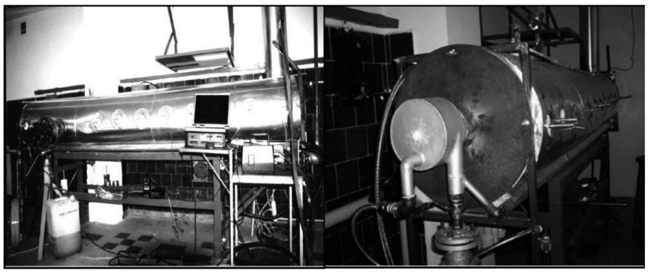


Fig. 2. General view of the experimental stand with control and measurement instrumentation

The study was conducted in a ceramic chamber, equipped with a gas spin-type burner. Primary air was injected to the burner with the use of a ventilator, while the secondary air, cold or warmed, was injected through the lance directly into the chamber. Gas and air flows were measured with the use of rotameters. Chamber temperature was measured by platinum/rhodium alloy thermocouple (type S), and the pressure by manometer VIGOTOR. Analysis of flue gas was performed with an auto flue gas analyzer TESTO 350 and TESTO 360 along with a set of sample conditioning TESTO 335. The combusted fuel was natural gas. The secondary combustion air was injected with the use of three types of lances, with a different way of air outflow. The scheme of the lances construction is shown in Fig. 3.

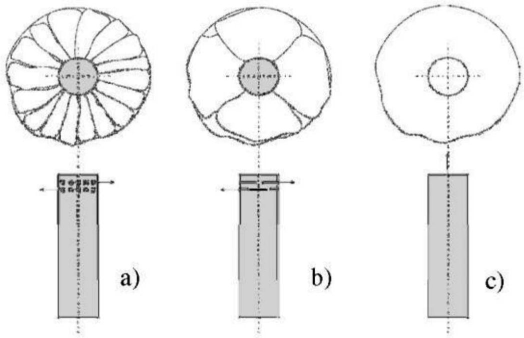


Fig. 3. Secondary air lances: a) lance with circumferential holes, b) lance with slotted outflow c) lance with frontal outflow

The simulation of the sample heating in the furnace chamber with a constant flow of heat from three directions x, y, z was also carried out. Measurements of the sample and heating chamber temperature were made with the use of infrared camera P-65 of Flir Company.

4.2. Numerical modeling test

4.2.1. The computational procedure with the use of the CHEMKIN software

Next to laboratory research the numerical calculations of air staging process were performed. The concentration of NO_x and CO in outlet of laboratory chamber was calculated with the use of a computational procedure. The numerical analysis was performed with support one of the subroutines of the CHEMKIN software, version 4.02 – „AURORA". The model examines the combustion processes occurring in so called "Perfectly Stirred Reactor". The data necessary to formulate boundary conditions in the modelling procedure were obtained from the results of preliminary research carried out in the laboratory chamber (Fig. 1). The results provided information on the distribution of temperatures and flow parameters, such as pressure and the quantities of implement gas and air streams. Prior to the calculation procedure creation of a diagram that included all processes analyzed in the issue was necessary. The next step was to prepare a batch file containing information about the conditions for carrying out the research, i.e.: mass stream and chemical composition of reacting substance, pressure, temperature, area of the analyzed section, residence time.

The basic chemical model of methane combustion was extended by reactions of nitrogen oxides formation. All considered reactions, with their equilibrium constants, were taken from the Miller-Bowman model. From among 235 reactions and 52 chemical compounds included in this model for research 126 reactions and 28 compounds were chosen. In the input file the equilibrium constant values, described by equation (1), were also included [8]:

$$k = AT^{B} exp(-E/R_{u}T). \tag{1}$$

The schematic diagram of the chamber used in modelling research reflects the actual experimental stand, and is shown in Fig. 4.

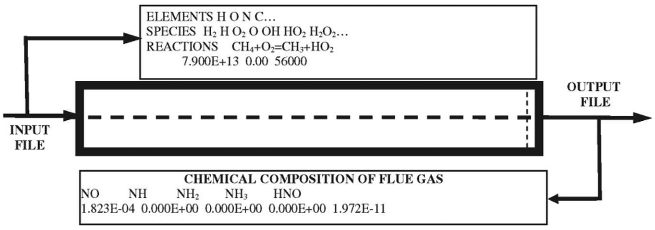


Fig. 4. A schematic diagram of the model test chamber

Distance between measurement points in the chamber for modelling studies follows the experiment, including its dimensions and locations of injection of the secondary air.

4.2.2. The computational procedure with the use of the FLUENT software

The fluid dynamics of flue gas flow in the combustion chamber was modelled in the FLUENT software. The computational (3D) space was discretized with the use of a non-structural grid composed of one million elements, being concentrated in the stirring chamber. The dimensionless parameter y^+, was taken into account during the mesh generation in order to determine the optional size of first cell adjacent to the chamber walls.

The following boundary conditions were assumed at the stirring chamber inlet:

► for air:

– inlet mass flow, $\dot{m}$ = 0.010392 kg/s,

– temperature, T = 290 K,

► for gas:

– inlet mass flow, $\dot{m}$ = 0.00055125 kg/s,

– temperature, T = 290 K.

The numerical integration of the model equations was based on the control volume procedure. The computation was carried out in steady conditions. As a criterion of convergence for all variables analyzed model the values of 10^{-6} for normalized residues were assumed.

Figure 5 shows a model of the experimental chamber with the distribution of temperatures on the chamber walls.

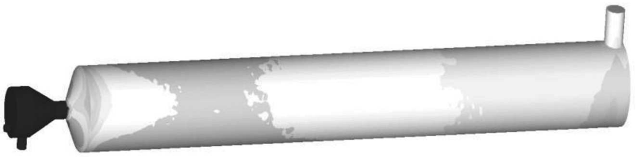


Fig. 5. View of the model with temperatures distributed at the walls of the chamber

System of model equations was solved with the use of sequential *(segregated)* solver.

5. Results

5.1. Results of laboratory research

The temperature measurements were performed in the heating chamber. The results of the temperature distribution as a function of time are presented in Figure 6. The minimum recorded temperature was 838°C for 57 second of measurement, whereas the maximum 841°C for 32 second.

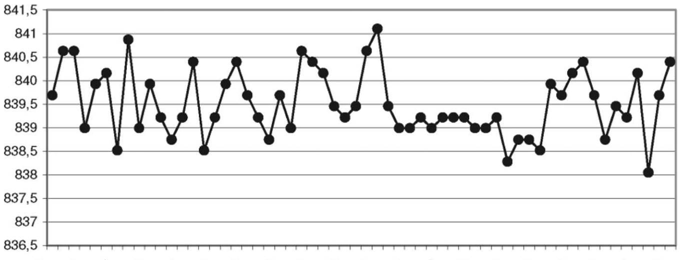
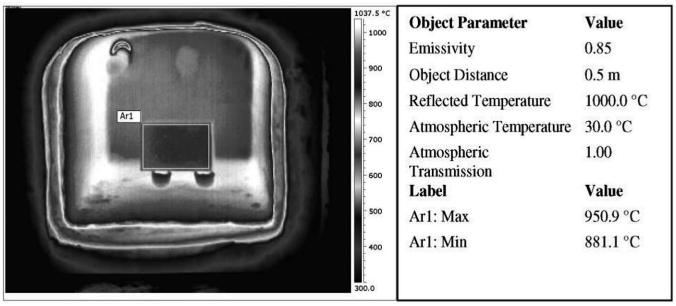


Fig. 6. Temperature distributions inside the chamber across observation time

Furthermore, the temperature measurement of the steel sample 2,5×2,5×4,0 cm in size heated in the chamber was conducted with the use of P-65 Flir camera. The measurement results are shown in Fig. 7.



Object Parameter	Value
Emissivity	0.85
Object Distance	0.5 m
Reflected Temperature	1000.0 °C
Atmospheric Temperature	30.0 °C
Atmospheric Transmission	1.00
Label	**Value**
Ar1: Max	950.9 °C
Ar1: Min	881.1 °C

Fig. 7. Measurement of sample temperature with the use of thermographic camera

The smallest recorded temperature of the sample was 881.1°C and highest was 950.9°C with the emissivity of 0.85.

In the scope of laboratory tests the measurements of chemical composition of flue gas in the flue duct from the chamber, in particular NO_x and CO for the different conditions of the carried out experiment, have been done, namely:

- air staging – introduction of secondary air through distribution pipes of various structures of the discharge nozzle, percentage of the secondary air was about 10%, and the lance was positioned in the chamber axis (Fig. 8 and 9),
- the air was heated to a temperature of 350°C – maximum contribution of heated air in the total air volume was 83% (Fig. 10 and 11).

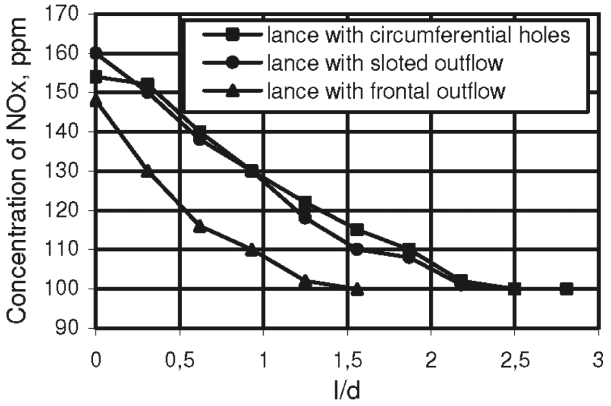


Fig. 8. The concentration of NO_x at the exit of the combustion chamber at $\lambda = 1.2$

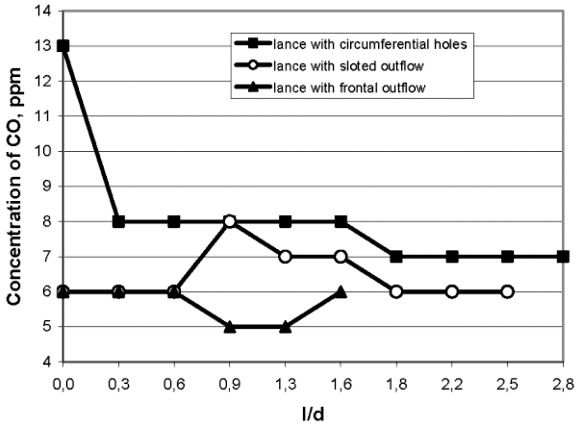


Fig. 9. The concentration of CO at the exit of the combustion chamber at $\lambda = 1.21$

The distribution of concentration of NO_x and CO are presented as a relation between the lance insertion depths along the chamber "l" to the diameter of the chamber "d" (Fig. 8 and 9). Figure 8 shows that both, the manner and the place of the secondary air injection, has a significant impact on the amount of formed NO_x. The NO_x concentration decreases with distance from the burner for all three design of lances. The lowest values were recorded for the lance with the outflow front, while the courses of concentrations for two other were very similar. Furthermore, Figure 9 shows that the lance structure has insignificant effect on CO concentration. The concentration values are very similar for all three lances.

Figure 10 shows that partial replacement of cold air by preheat air affect the NO_x and CO concentrations increase in the flue gas. The introduction of heated air, due to the rising temperature in the chamber, significantly changes the concentration of nitrogen oxides. The 83% percentage of heated air cause the NO_x increases twice as regards the initial conditions, and reach a value of 328 ppm. Changes in NO_x concentration was also analyzed as a function of excess air and the cold as well as the preheat air (Fig. 11).

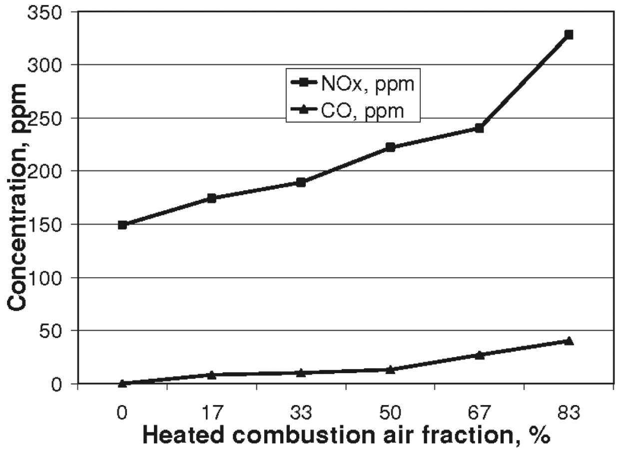


Fig. 10. The influence of the heated air contribution on NO_x and CO concentration in the flue gas λ = 1.06

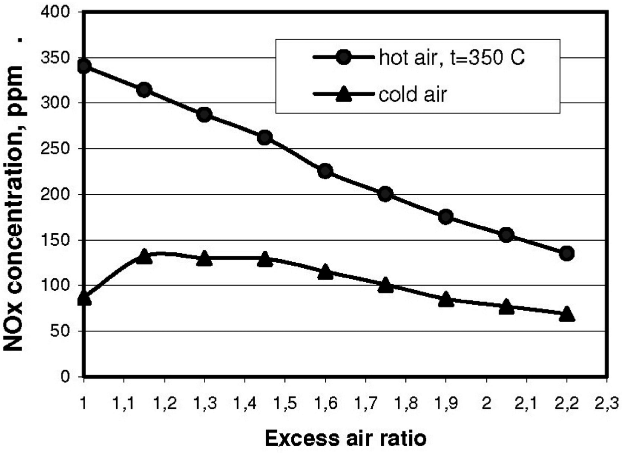


Fig. 11. Dependence of NO_x concentration on the excess air ratio λ for cold and hot air

As can be seen in the Fig. 11 the concentrations of NO_x are lower in the case of cold air introduction. During supplying of hot air the concentration of NO_x decreases when air excess increases. At λ=1.0 the NO_x concentration is equal 350 ppm, while at λ=2.2 it is equal 140 ppm. In turn, during combustion with cold air the concentrations of NO_x initially increase up to 140 ppm at λ=1.1 and at λ=2.2 it decreases reaching a value equal 65 ppm.

5.2. Results of numerical modelling

The results of numerical simulations are shown in Fig. 12-14 and Fig. 15-16. They were caculated using Chemkin and Fluent softwares, respectively. In the Fig. 12. the distribution of temperature across the length of the chamber

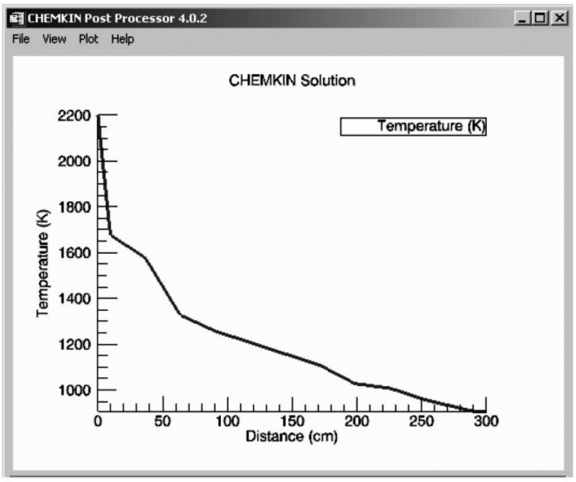


Fig. 12. Temperature distribution across the length of the chamber

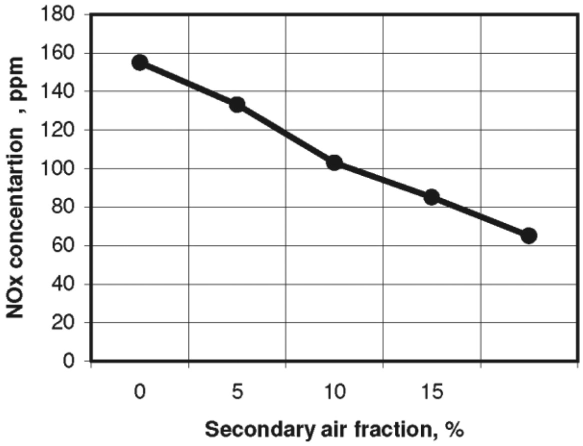


Fig. 13. The distribution of NO_x concentration in dependence of secondary air fraction

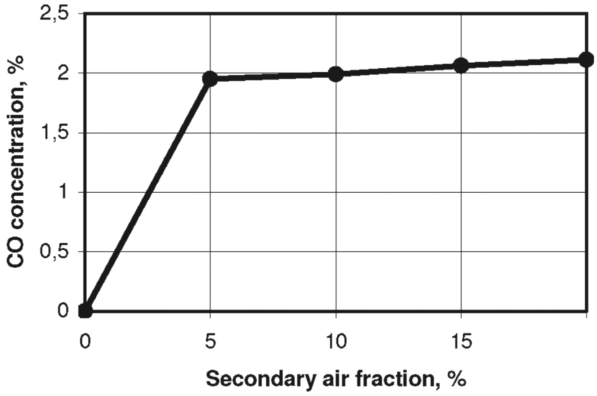


Fig. 14. The distribution of CO concentration in dependence of secondary air fraction

is presented. The distribution of NO_x and CO concentrations in dependence of secondary air fraction is shown in Fig. 13-14. The distribution of velocity in the longitudinal section of furnace for different variant is presented in Fig. 15-16.

The change in NO_x concentration, presented in Figure 13 and 14, shows that with the increase of the secondary air content, the concentration of NO_x in the flue gas decreases. However, the opposite situation occurs in the case of carbon monoxide (Fig. 14). The content of secondary air at a level of 5% results in an increase of CO concentration from 0 to 2%. In addition, with the increase in the content of secondary air, the concentration of CO slightly increases. In the range of the calculations with the use of CHEMKIN software, the temperature profile in the experimental chamber, including the determination of maximum temperatures prevailing in the flame (Fig. 12), was estimated. The maximum temperature was estimated at a level of 2200 K, which is close to the calorimetric temperature of methane combustion. The results of calculations of the velocity distribution in the experimental chamber, presented in Figure 15 and 16, show a clear effect of presence of the lance on the velocity in the chamber. In case of the lance use, the obtained values ??are much higher than those without lance (Fig. 15).

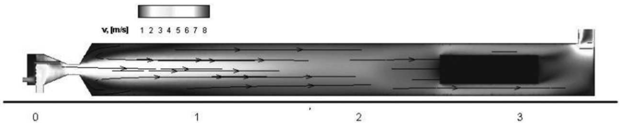


Fig. 15. Velocity fields of the gas in the longitudinal section of the furnace with power lines – a variant without a lance

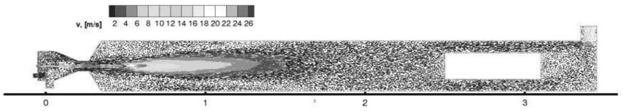


Fig. 16. Distribution of velocity vectors in the longitudinal section of furnace – a variant with a lance

6. Model studies for real facilities

The obtained results of the experimental and model research carried out in the experimental chamber were extended by research on a real ”object”, which was a three-row tunnel pusher furnace. All technical data related to the operation of both furnaces were supplied by the ‘user’. The most important parameters the applied for computation in the model research are shown in Table 1.

TABLE 1
The technical parameters of the sheet hardening furnace

Zone	Supplied fuel flow m^3/s	Supplied air flow m^3/s	Temperature °C	Zone length m	Flue gas velocity m/s
Zone I	0.208	2.54	820-860	8.25	3.33
Zone II	0.125	1.52	860-900	8.25	2.23
Zone III	0.058	0.707	880-910	8.25	1.497
Zone IV	0.058	0.683	900-940	8.25	1.193
Zone V	0.08	0.683	910-930	8.25	0.84
Zone VI	0.058	0.495	920	8.25	0.35

It was assumed for both furnaces that the flue gas flowed in a counter current system, as in the case of heat furnaces under real conditions. The hardening furnace was divided into six contractual regulatory zones.

Numerical calculations with the use of Fluent and Chemkin softwares were performed for the actual heating chamber. Model of the chamber used to calculate the combustion chemistry is shown in Fig. 17, and model for the calculation of the flow in Fig. 18.

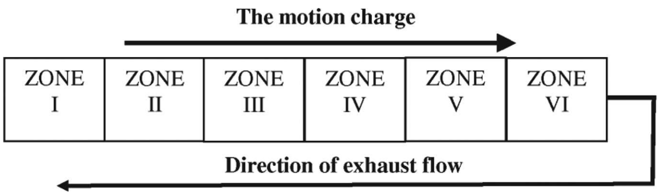


Fig. 17. Heating furnace model

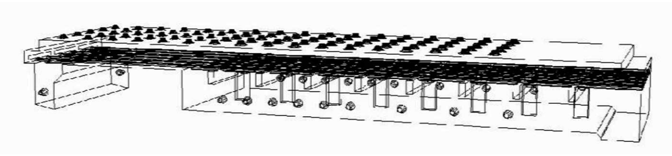


Fig. 18. View of the heating chamber with spaced burners and charge

Distribution of gas velocity in the chamber is shown in Fig. 19.

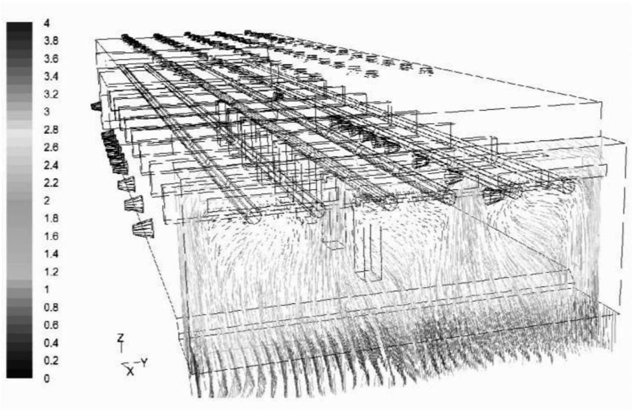


Fig. 19. Distribution of flue gas velocities at the outflow of the furnace

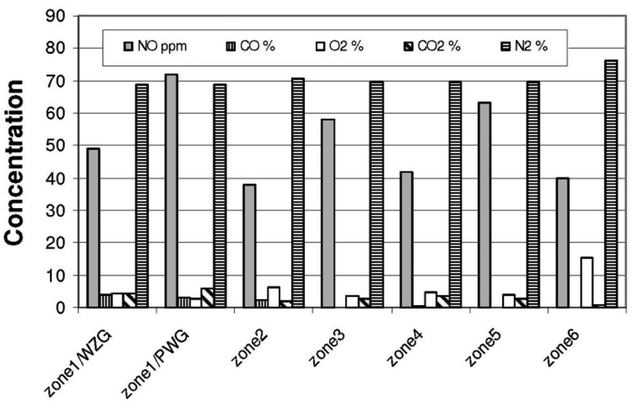


Fig. 20. Composition of flue gas for single burners at the end of each zone calculated by CHEMKIN

The results of the calculations with the use of Chemkin software are shown in Fig. 20. The model of the furnace, presented in Figure 17, included six heating zones. For each zone the chemical analysis of the flue gas was determined by the numerical calculations. Selected products of combustion, such as NO, O_2, CO_2 and N_2 (Fig. 20) have been analyzed in detail. The greatest concentration of NO is observed in zone I (72 ppm) for the PWG burner, while the smallest in zone II (38 ppm). Measurements of the composition of flue gas in the range of CO show that the highest concentrations occur in zone I and II, and even reach the level of 3.8% in the zone I for the WZG burner. The observed discrepancies in the concentrations of both NO and CO, and the other compounds, are the result of the prevailing conditions of flow and temperature in each zone of the furnace. The results of calculations are comparable with the values of the concentrations typical for this type of objects. The high conformity of results was also obtained for the velocity distribution in the furnace chamber (Fig. 19). These velocities, depending on the considered zone, are within the range of 0.1 to 4 m/s.

7. Summary

Calculations of combustion chemistry and flue gases flow with the use of Chemkin and Fluent softwares can be applied for the modernization of heat furnaces. Experimental measurements and numerical calculations were conducted for the laboratory chamber and actual object. As the real object tunnel kiln with countercurrent flow of the flue gas was chosen. This choice was dictated by the possibility of obtaining specific data for the furnace and the fact that the furnace was after a capital repair (replacement of lining, changing of the firing – coke oven gas had been replaced by rich natural gas, the introduction of automatic computer regulation of the oven). Laboratory research were conducted in the chamber having a fairly stable value of temperature across its length with the use of different constructions of air lances. Flat temperature distribution was obtained for lance with circumferential holes and lance with slotted outflow. Change of the lance position resulted in reduction of pollutants concentration (decrease of NO_x concentration and stable concentration of CO). Application of the hot air to combustion chamber caused an emission increase.

The combustion diagnostics carried out in this paper, for both the experimental chamber and the reheating furnace, provided valuable insights and allowed to formulate the following conclusions:

- The use of air staging has significant impact on the amount of formed pollutants, especially NO_x and CO.
- NO_x concentration decreases with the increase in the content of the secondary air, while CO concentration increases (Fig. 13 and 14).
- The lance design and place of supply of secondary air is of significant importance. NO_x concentration decreases with the distance increase from the burner (Fig. 3) for all the analyzed construction of lances. The lowest values of nitrogen oxides were observed for lance with the frontal outflow.
- The concentration of CO is at a comparable level, regardless of the lance type.
- The secondary air heating has a significant impact on the concentrations of NO_x and CO in the flue gas. The concentrations of NOx and CO increase with the rise of temperature of heated secondary air (Fig. 10). For the constant temperature of the heated air at a level of 350°C, the concentration of NO_x is lower for higher values of excess air ratio (Fig. 11).
- Performed numerical calculations, due to the high similarity of the experimental results, prove the correctness of the assumptions applied in the calculations. Due to the above, the results of calculations are utilitarian and can be the basis for the processes optimization, aiming to minimize the pollutants emission in industrial reheating furnaces.

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