THE REDUCTION OF NITROGEN MONOXIDE CONCENTRATION TO THE COALS HAVING A HIGH CONTENT OF ASH

I. PÎŞĂ, C. NEAGA*

În lucrare autorii şi-au propus studierea formării de NO_X la cărbunii cu conţinut ridicat de cenuşă. În primul rând s-a determinat timpul de uscare funcţie de masa minerală externă şi de diametrul iniţial al particulei de cărbune. În al doilea rând a fost cuantificată influenţa masei minerale asupra concentraţiei de oxizi de azot.

In this paper, the authors analyse the generation of NOx in the coals having a high content of ash. On the one hand, the drying time has been determined, depending of the external mineral mass and the initial diameter of the coal particle. On the other hand, the influence of the mineral mass over the concentration of nitrogen oxides has been quantified.

Keywords: steam generators, combustion, nitrogen oxides, ballast.

Introduction

The authors study the burning of the coals having a high content of ash which derives from the mineral mass. The mineral mass of the coal consists of:

- the internal mineral mass which derives from the mineral mass of the genetic material (the combustion of the particles leads to the appearance of the internal ash which is carried from the particles surface and included in the corresponding gas phase.)
- the external mineral mass which derives from the sterile drawn in the coal extraction (after the combustion it transforms into the external ash and it represents about 90% from the total mineral mass.)

The methods of approaching the elementary analysis of a test carried from the raw coal bunker do not make evident the existence of such fully inert particles. The mineral mass of the initial particle having the diameter δ_{oc} is composed of the internal mineral mass and of the external mineral mass. The extraction technology of lignite (by uncovering) leads to the idea that the external mineral mass consists of separate mineral particles (after grinding). These accompany the rest of the particle which is burning and which contains only the internal mineral mass. This

* Reader; Prof., Dept. of Classical and Nuclear Thermal Power Equipment, University POLITEHNICA of Bucharest, Romania

is uniformly distributed and after burning it passed into the combustion gases. If the fraction corresponding to the external mineral mass is noted by x_e (usually $x_e \approx 0.90$ [1]) and those mentioned above are taken into consideration, one can reach the conclusion that after the external mineral mass (the ash) is removed, the coal is enriched and will have the following elementary analysis:

$$C^i = f_{0-i}C^0 \;,\%;\; H^i = f_{0-i}H^0 \,,\; \%;\; S_c^i = f_{0-i}S_c^0 \,,\; \%;\; N^i = f_{0-i}N^0 \,,\; \%;\; O^i = f_{0-i}O^0 \,,\; \%;$$
$$A^i = f_{0-i}(1-x_e)A^0 \,,\; \%;\; W_t^i = f_{0-i}W_t^0 \,,\; \%, \tag{1}$$

where the transformation factor f_{0-I} is given by the expression:

$$f_{0-i} = \frac{100}{100 - x_e \cdot A^0} \tag{2}$$

Taking into account the transformation factor, the values of the imbibition and hygroscopic moistures (together form the total humidity) modify, as follows:

$$W_i^i = f_{0-i}W_i^0 \,,\; \%;\; W_h^i = f_{0-i}W_h^0 \,,\; \% \tag{3}$$

The technical (immediate) analysis of the coal (the content of volatile and of fix coal) is also influenced by the transformation factor f_{0-i}:

$$V^i = f_{0-i}V^0 \;,\; \%;\; C_f^i = f_{0-i}C_f^0 \;,\; \%; \tag{4}$$

The removed mineral mass, after the combustion of the remaining combustible, leads to the formation of n_a particles of ash. The jet of dust introduced into the furnace consists of plenty of such independent “units” (Fig. 1). A “unit” is formed by a particle which burns accompanied by the “cloud” of ash particles. If the combustion process includes the drying phase, the total burning time is divided into four areas (Fig. 2), compared with three zones [6], as follows: the drying area, the ignition area, the area of combustion of volatile substances and the zone of finishing the combustion.

The drying area Z_0 corresponding to the interval $0<\tau<\tau_1$ where τ_1 is the time when the dust humidity, $w_p = 0$. (it is also named drying time).

The ignition area Z_i corresponding to the interval $\tau_1 < \tau < \tau_2$, where τ_2 is the moment when the introduction of the secondary air begins. The processes from this area consist mainly of the emission of the volatile substances. This moment is situated after the moment τ_{aprv}, corresponding to the moment of the ignition of the volatile substances. This is the moment of the beginning of formation of the monoxide nitrogen from coal NO_c.

The area of combustion of volatile substances corresponding to the interval $\tau_2 < \tau < \tau_3$. Zone Z_2 is characterized by the introduction only of the secondary air or the secondary air together with the recirculated combustion gas from furnace end-part (r_{evs}), after a time imposed law (in case of the paper a linear law). The generation of NO_c continues, being dragged by the introduction of the secondary air in a succession of stages. Now, the nitrogen monoxide from the combustion air appears; it is essentially depending on the temperature. There is also present the burning of base of coke, a process carried on both in parallel with the combustion of the volatiles and after that. Z_1 and Z_2 zones unfold either simultaneous or they succeed one another.

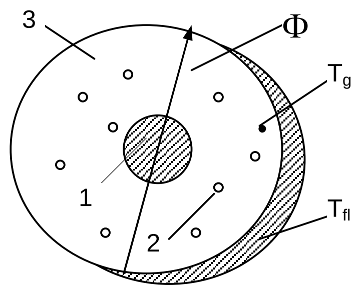

Fig..1. Schematic representation of "one unit".
1 – coal particles; 2 – cloud of ash particles; 3 – diameter of gas cover of "one unit", Ø

The finishing zone of the combustion corresponding to the interval $\tau_3 < \tau < \tau_a$. This area noted Z_3 is the area when the combustion process is finished. The combustion air has been completely introduced. The particle burns fully up to the ash particle which, practically, derives from the internal mineral mass.

1. The mathematical model for Z_0

The equations characterizing the area Z_0 are:

- for the drying dynamics:

$$\frac{dW_p}{d\tau} = -\frac{6}{r\delta_0\rho_{ap}}\left[a_{cb}\sigma_o\left(T_{fl}^4 - T^4\right) + \alpha_{gc}\left(T_g - T\right)\right]\frac{kg_{apa}}{kg \cdot s} \quad (5)$$

where W_p is the current humidity of the coal dust, [$kg_{humidity}/kg_{coal}$]; r – the latent vaporizing heat, r = 2258 kJ/kg; ρ_{ap} – the apparent density, ρ_{ap} = 900 kg/m³; δ_0 – the diameter of the burning particle, m (constant in this area); a_{cb} – the energetic coefficient of coal emission (it can be imposed a_{cb} = 0.8); α_{gc} – the gas convection coefficient – particle, kW/(m²·K); the convection coefficient α_{gc} is calculated by using the relationship [2]:

$$\alpha_{gc} = \frac{2}{\delta_0}\left(0.8805 \cdot 10^{-7} T_g - 0.124 \cdot 10^{-5}\right) \quad (6)$$

At the initial moment,

$$\tau = 0.\, W_p = W_{p_0} = W_h^i = \frac{0.01 W_h^0}{1 - x_e \dfrac{A^0}{100}}, \quad (7)$$

After $\tau = \tau_1$ (τ_1 is the drying time) $W_p = 0$.

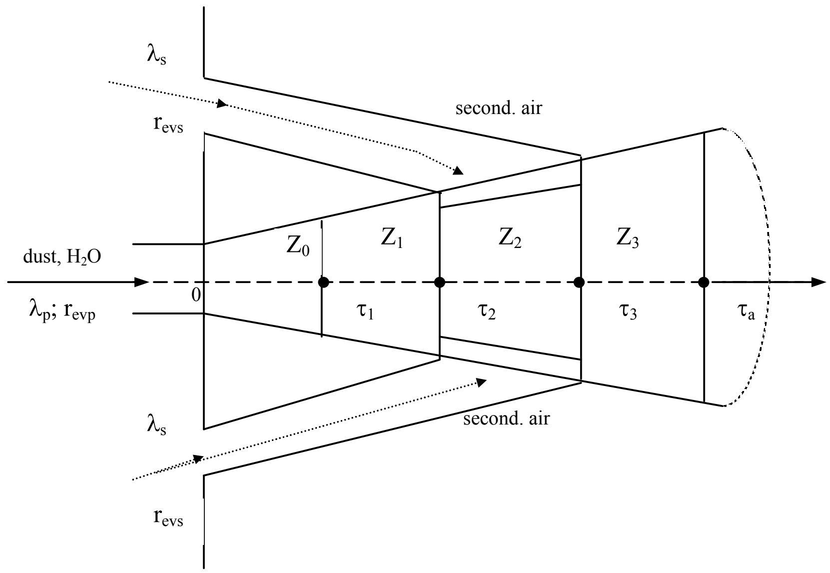

Fig.2. The structure of the pulverized jet coal

- for the variation of the temperature of the gas phase:

$$\frac{dT_g}{d\tau} = \left\{ -\left[r_i\left(\xi + \lambda_i - 1\right)\frac{V_{aum}^0}{\tau_a} + 1.242 \cdot \frac{dW_p}{d\tau} \right]\left(T_g - 273\right) - \right.$$
$$- \frac{6\alpha_{gc}}{\delta_0 \rho_{ap} c_g}(T_g - T) - \frac{i^{"}}{c_g} \cdot \frac{dW_p}{d\tau} + + r_i\left(\xi + \lambda_i - 1\right)\frac{V_{aum}^0}{\tau_a} \cdot \left(T_{fl} - 273\right) - \quad (8)$$
$$\left. -6 \cdot \frac{n_a \alpha_{ga} \delta_a^2}{\delta_0^3 \rho_{ap} c_g}(T_g - T_a) + 6 \cdot \frac{\Phi^2 \sigma_0 a_g}{\delta_0^3 \rho_{ap} c_g}\left(T_{fl}^4 - T_g^4\right) \right\} / V_{gZ_0}$$

where V_{gZ_0} is the gas volume with reference to one kilogram of drying coal ; it is calculated with the relation :

$$V_{gZ_0} = \lambda_p V_{aum}^0 + 1.242 W_i^i + \left[r_f\left(\xi + \lambda_f - 1\right) + r_{evp}\left(\xi + \lambda_{ev} - 1\right) + \right.$$
$$\left. + r_i\left(\xi + \lambda_i - 1\right)\frac{\tau}{\tau_a} \right] V_{aum}^0 + 1.242 W_p, \frac{m_N^3}{kg} \quad (9)$$

where λ_p is the excess coefficient of primary air; λ_i – the coefficient of air excess in the furnace at the level of burners; λ_{ev} – the coefficient of air excess at the evacuation; r_i ,r_f – the recirculating degree from the burning inlet and from furnace end-part, respectively; W^i_i – the imbibition humidity (it is calculated with the relation 3); V^0_{aum} – the theoretical volume of wet air that is corrected with the transformation factor, f_{0-i}; τ_0 – the total time of combustion, initially admitted between 0.5÷1.5 seconds, lately its value being checked up; c_g – the heat specific to the burning gases (it is admitted constant, c_g=, =1.35 $kJ/(m_N^3 \cdot K)$); i”- the enthalpy of the saturated steam, i”=2676 kJ/kg; α_{ga}-the convection coefficient from gases to the ash particles; $\alpha_{ga}=2\lambda_g/\delta_a$, where $\delta_a=20\cdot10^{-6}$m (the diameter of the ash particle); T_a – the temperature of the ash, K; a_g – the energetic coefficient of the gas emission inside the cover, at the temperature T_g, a_g = 0.3÷0.4 [5]; T – the temperature of the particle (373 K); Φ – the diameter of the cover [3], m; this diameter is calculated by the relation:

$$\Phi = \delta_0 \left(\rho_{ap} V_{gZ_0} \cdot \frac{T_g}{T_0} \right)^{1/3}, \tag{10}$$

where T_0 is the reference temperature, T_0=273 K and the number of ash particles, n_a is calculated by the relation:

$$n_a = \frac{\rho_c \cdot x_e \cdot A^0}{100 \cdot \rho_a} \cdot \left(\frac{\delta_{0c}}{\delta_a} \right)^3, \tag{11}$$

where ρ_a is the ash density, ρ_a = 1500 kg/m^3.

- for the variation of the temperature of the ash particles:

$$\frac{dT_a}{d\tau} = \frac{6}{\rho_a \delta_a c_a}\left[\sigma_0 a_a \left(T_{fl}^4 - T_a^4\right) + \alpha_{ga}\left(T_g - T_a\right)\right] + \frac{6\delta_0 \sigma_0 a_{ca} \varphi_{can}}{n_a \delta_a^3 \rho_a c_a}\left(T^4 - T_a^4\right), [K/s] \tag{12}$$

c_a is the specific heat of ash, kJ/(kg·K); it is admitted the constant, c_a = 1 kJ/(kg·K); a_a – the energetic emission coefficient of ash, a_a=0.7; a_{ca} the blackness coefficient of the system particle-ash [4], $a_{ca}\approx0.7$; φ_{can} – the mutual radiation coefficient between the particle and the ash, φ_{can}= 0.2 [5].

2. The mathematical model for Z_1

The equations characterizing this area are:

- for the dynamics of volatiles emission:

$$\frac{dV}{d\tau} = 150000 \cdot \left(V^i - V\right) \cdot e^{-\frac{8900}{T}}, \text{[kg/(kg.s)]}; \tag{13}$$

- for the dynamics of volatile substances combustion:

$$\frac{dW}{d\tau} = 690 \cdot (V - W) \cdot C_{Z_1} \cdot e^{-\frac{4650}{T_g}} + \frac{W}{V_{gZ_1}} \cdot \frac{dV_{gZ_1}}{d\tau}, \text{[kg/(kg·s)]}, \tag{14}$$

where the gases volume of this zone is given by the relation:

$$V_{gZ_1} = \lambda_p \cdot V^0_{aum} + 1.242W^i_t + \left[r_f\left(\xi + \lambda_f - 1\right) + r_i\left(\xi + \lambda_i - 1\right)\frac{\tau}{\tau_a} + r_{evp}\left(\xi + \lambda_{ev} - 1\right)\right]V^0_{aum} + \left(V - W\right)v_v + \\ + \left(1 - \frac{\delta^3}{\delta_0^3}\right)(V^0_g - V^0_{aum} - 1.242W^i_t) - \left[\left(1 - \frac{\delta^3}{\delta_0^3}\right)V - W\right]\left(5.6H_v + 0.8N_v + 0.7O_v\right),\ [m^3_N / kg] \tag{15}$$

where v_v is the specific volume of the volatiles, v_v=1.307 m^3_N / kg [6].

For the volatiles with medium composition (H_v, N_v, O_v – mass fractions of hydrogen, nitrogen and oxygen from volatiles), the factor $5.6H_v + 0.8N_v + 0.7O_v = 0.86$ – represents the volume growth of the combustion gases at the volatiles burning [3]. The value of derivate $dV_{gZ_1} / d\tau$ is given by the following relation:

$$\frac{dV_{gZ_1}}{d\tau} = r_i\left(\zeta + \lambda_i - 1\right)\frac{1}{\tau_a} \cdot V^0_{aum} + \left(\frac{dV}{d\tau} - \frac{dW}{d\tau}\right) \cdot v_v - \frac{3\delta^2}{\delta_0^3} \cdot \left(V^0_g - V^0_{aum} - 1.242W^i_t\right)\frac{d\delta}{d\tau} - \\ -0.86\left[-\frac{3\delta^2}{\delta_0^3}V\frac{d\delta}{d\tau} + \left(1 - \frac{\delta^3}{\delta_0^3}\right)\frac{dV}{d\tau} - \frac{dW}{d\tau}\right],\ \frac{\mathrm{m^3_N}}{\mathrm{kg \cdot s}} \tag{16}$$

and the concentration of oxygen in this zone is :

$$C_{Z_1} = \left\{\lambda_p + r_g\left(\lambda_f - 1\right) + r_{evp}\left(\lambda_{evp} - 1\right) + r_i\left(\lambda_i - 1\right)\frac{\tau}{\tau_a} - \left(1 - \frac{\delta^3}{\delta_0^3}\right) + \\ + \left[\left(1 - \frac{\delta^3}{\delta_0^3}\right)V - W\right]\frac{M_{O_{2v}}}{M_{O_2}}\right\} \cdot \frac{M_{O_2}}{V_{gZ_1}}, \left[\frac{kgO_2}{m^3_N}\right] \tag{17}$$

where the mass of oxygen for burning one kilo of ennobled coal, M_{O_2} and the mass of oxygen for burning the volatiles, $M_{O_{2V}}$ will be corrected with the transformation factor f_{0-i}.

- for the variation of the temperature of the coal particle:

$$\frac{dT}{d\tau} = \left\{\left[c_v\left(T - 273\right) + Q_v\right]\frac{dV}{d\tau} - \frac{3}{\delta}\left\{\left(V^i - V\right)\left[c_v\left(T - 273\right) + Q_v\right] + \\ + C^i_f\left[c_{c_f}\left(T - 273\right) + Q_{c_f}\right] + c_a A^i\left(T - 273\right)\right\}\frac{d\delta}{d\tau} + \frac{6}{\rho_{ap} \cdot \delta} \cdot \\ \cdot \left\{\sigma_0 a_c\left(T^4_{fl} - T^4\right) + \alpha_{gc}\left(T_g - T\right) + k \cdot C_{pZ_1}\frac{T_0}{T_g} \cdot \left[c_{O_2}\left(T_g - 273\right) - \frac{44}{32}c_{O_2}\left(T - 273\right)\right] - \\ -\sigma_0 a_{ca}\varphi_{can}\left(T^4 - T^4_a\right)\right\}\right\} / \left[\begin{matrix} c_v\left(V^i - V\right) + \\ + c_{c_f}C^i_f + c_a A^i \end{matrix}\right], \left[\frac{K}{s}\right] \tag{18}$$

where k is the constant of the kinetic coal combustion speed and the concentration of oxygen on the surface of coke particle which burn in Z_1 is:

$$C_{pZ_1} = \frac{C_{Z_1}}{1 + \frac{k\delta}{D} - 0.75\frac{k\delta^2}{D \cdot \Phi}}, \tag{19}$$

where D is the diffusion coefficient, [m^2/s]; the diameter of the cover Φ in this area results from the relation 10, in which V_{gZ_0} is replaced with V_{gZ_1}.

- for the variation of the temperature of the gas phase:

$$\begin{aligned}\frac{dT_g}{d\tau} = \Bigg\{ & -c_g\left(T_g - 273\right)\frac{dV_{gZ_1}}{d\tau} - \left(\frac{dV}{d\tau} - \frac{dW}{d\tau}\right)Q_v - \frac{6\delta^2\alpha_{gc}}{\delta_0^3\rho_{ap}}\left(T_g - T\right) - \\ & -\frac{6\delta_a^2\alpha_{ga}}{\delta_0^3\rho_{ap}}\left[n_a + \frac{\left(\delta_0^3 - \delta^3\right)\rho_{ap}A^i}{\delta_a^3\rho_a}\right]\left(T_g - T_a\right) - \frac{6\delta^2}{\delta_0^3\rho_{ap}}kC_{pZ_1}\frac{T_0}{T_g}\cdot \\ & \cdot\left[c_{O_2}\left(T_g - 273\right) - \frac{44}{32}c_{O_2}\left(T - 273\right)\right] + r_i c_g\left(\xi + \lambda_i - 1\right)\left(T_{fl} - 273\right)\frac{V_{aum}^0}{\tau_a} + \\ & + \frac{6\Phi^2}{\delta_0^3\rho_{ap}}a_g\sigma_o\left(T_{fl}^4 - T_g^4\right)\Bigg\} / \left(c_g V_{gZ_1}\right), [K/s]\end{aligned} \tag{20}$$

- for the variation of the temperature of external ash particles (around the burning particle):

$$\begin{aligned}\frac{dT_g}{d\tau} = \Bigg\{ & -c_g\left(T_g - 273\right)\frac{dV_{gZ_1}}{d\tau} - \left(\frac{dV}{d\tau} - \frac{dW}{d\tau}\right)Q_v - \frac{6\delta^2\alpha_{gc}}{\delta_0^3\rho_{ap}}\left(T_g - T\right) - \\ & -\frac{6\delta_a^2\alpha_{ga}}{\delta_0^3\rho_{ap}}\left[n_a + \frac{\left(\delta_0^3 - \delta^3\right)\rho_{ap}A^i}{\delta_a^3\rho_a}\right]\left(T_g - T_a\right) - \frac{6\delta^2}{\delta_0^3\rho_{ap}}kC_{pZ_1}\frac{T_0}{T_g}\cdot \\ & \cdot\left[c_{O_2}\left(T_g - 273\right) - \frac{44}{32}c_{O_2}\left(T - 273\right)\right] + r_i c_g\left(\xi + \lambda_i - 1\right)\left(T_{fl} - 273\right)\frac{V_{aum}^0}{\tau_a} + \\ & + \frac{6\Phi^2}{\delta_0^3\rho_{ap}}a_g\sigma_o\left(T_{fl}^4 - T_g^4\right)\Bigg\} / \left(c_g V_{gZ_1}\right), [K/s]\end{aligned} \tag{21}$$

- for the variation of the diameter of the coal particle:

$$\frac{d\delta}{d\tau} = \left[\frac{\delta}{3}\frac{dV}{d\tau} - \frac{2}{\rho_{ap}}kC_{pZ_1}\frac{T_0}{T_g}\left(\frac{1}{M_{O_2} - vM_{O_{2v}}}\right)\right] / \left(C_f^i + V^i - V + A^i\right), [\text{m/s}], \tag{22}$$

3. The mathematical model for Z_2

This area is characterized by the introduction only of the secondary air or the secondary air together with the recirculated gases from the end-part of the steam generator (r_{evs}). This zone corresponds to the interval $\tau_2 \le \tau \le \tau_3$. The secondary air introduction period is $\Delta\tau$ ($\Delta\tau = \tau_3 - \tau_2$).

The dynamics of emission of volatiles, the dynamics of combustion of volatiles and the variation of the temperature of coal particle have the same expression as relations 13, 14, respectively 18. The values of the gas volume, of the oxygen concentration in the gas stage and of the oxygen concentration on the surface of the coke particle have the following calculation formulae:

- for the volume of the gas phase in Z_2:

$$V_{gZ_2} = V_{gZ_1} + \left[\lambda_i - \lambda_p + r_{evs}\left(\xi + \lambda_{ev} - 1\right)\right]V_{aum}^0 \frac{\tau - \tau_1}{\Delta\tau}; \tag{23}$$

- for the average concentration of oxygen in the gas cover:

$$C_{Z_2} = \left\{C_{Z_1}V_{gZ_1} + \left[\lambda_i - \lambda_p + r_{evs}\left(\lambda_{ev} - 1\right)\right]\frac{\tau - \tau_1}{\tau_2 - \tau_1} M_{O_2}\right\}\frac{1}{V_{gZ_2}}; \tag{24}$$

- for the diameter of the cover Φ (which enters into the relation of calculation of C_{pZ_2}):

$$\frac{\pi\Phi^3}{6} = \frac{\pi\delta_0^3}{6}\rho_{ap}V_{gZ_2}\frac{T_g}{T_0}. \tag{25}$$

Other relations characterizing this area are:

- for the variation of the temperature of the gas phase:

$$\begin{aligned}\frac{dT_g}{d\tau} = \Bigg\{ & -c_g\left(T_g - 273\right)\frac{dV_{gZ_2}}{d\tau} - \left(\frac{dV}{d\tau} - \frac{dW}{d\tau}\right)Q_v - \frac{6\delta^2\alpha_{gc}}{\delta_0^3\rho_{ap}}\left(T_g - T\right) - \\ & - \frac{6\delta_a^2\alpha_{ga}}{\delta_0^3\rho_{ap}}\left[n_a + \frac{\left(\delta_0^3 - \delta^3\right)\rho_{ap}A^i}{\delta_a^3\rho_a}\right]\left(T_g - T_a\right) - \frac{6\delta^2}{\delta_0^3\rho_{ap}}kC_{pZ_2}\frac{T_0}{T_g}\cdot \\ & \cdot\left[c_{O_2}\left(T_g - 273\right) - \frac{44}{32}c_{O_2}\left(T - 273\right)\right] + r_i\left(\xi + \lambda_i - 1\right)\left(T_{fl} - 273\right)c_g\frac{V_{aum}^0}{\tau_a} + \\ & + \left[\left(\lambda_i - \lambda_p\right)c_{aum}t_p^{"} + r_{evs}\left(\xi + \lambda_{ev} - 1\right)c_g t_{ev}\right]V_{aum}^0\frac{\tau - \tau_1}{\tau_2 - \tau_1} + \\ & + \frac{6\Phi^2 a_g\sigma_o}{\delta_0^3\rho_{ap}}\left(T_{fl}^4 - T_g^4\right)\Bigg\} / \left(c_g V_{gZ_3}\right), [K/s]\end{aligned} \tag{26}$$

where $$\frac{dV_{gZ_2}}{d\tau} = \frac{dV_{gZ_1}}{d\tau} + \left[r_{evs}\left(\xi + \lambda_{ev} - 1\right)\right] \cdot \frac{V^0_{aum}}{\Delta\tau} \qquad (27)$$

- for the variation of the temperature of the external ash the relation 21;
- for the variation of the diameter of the particle which burns the relation 22, with the remark that C_{pZ_1} is replaced with C_{pZ_2} and in the equation of the kinetic of nitrogen volatilization is introduced V_{gZ_2}. The rest of the equations of the mathematical model remain unchanged.

4. The mathematical model for Z_3

This area is a zone where the finishing of combustion takes place At the moment of start, the entire quantity of air for combustion has been introduced and all the volatiles have been released and burnt. Under these circumstances, the relations are much simplified in this area comparison with the previous zone, because:

$$\frac{dV}{d\tau} = 0; \ \frac{dW}{d\tau} = 0; \ \frac{\tau - \tau_1}{\tau_2 - \tau_1} = 1; \ V = W = V^i \qquad (28)$$

The volume of the gas stage of area Z_3, the concentration of oxygen in this zone and the concentration of oxygen on the surface of the coke particle are given by the relations:

$$V_{gZ_3} = \left[\lambda_i + r_g\left(\xi + \lambda_f - 1\right) + r_i\left(\xi + \lambda_f - 1\right)\frac{\tau}{\tau_a} + \left(r_{evp} + r_{evs}\right)\left(\xi + \lambda_{ev} - 1\right)\right] \cdot$$
$$\cdot V^0_{aum} + 1.242W^i_t + \left(V - W\right)v_v + \left(1 - \frac{\delta^3}{\delta_0^3}\right)\left(V^0_g - V^0_{aum} - 1.242W^t_i\right) - \qquad ; \qquad (29)$$
$$-0.86\left[\left(1 - \frac{\delta^3}{\delta_0^3}\right)V - W\right], \ [m^3_N / kg]$$

$$C_{Z_3} = \left\{\lambda_i + r_f\left(\lambda_f - 1\right) + \left(r_{evp} + r_{evs}\right)\cdot\left(\lambda_{ev} - 1\right) + r_i\left(\lambda_i - 1\right)\frac{\tau}{\tau_a} - \left(1 - \frac{\delta^3}{\delta_0^3}\right) + \right.$$
$$\left. + \left[1 - \left(\frac{\delta^3}{\delta_0^3}\right)V - W\right]\right\} \cdot \frac{M_{O_2}}{V_{gZ_3}}, \left[\frac{kgO_2}{m^3_N}\right] \qquad ; \qquad (30)$$

$$C_{pZ_3} = \frac{C_{Z_3}}{1 + \frac{k\delta}{D} - 0.75\frac{k \cdot \delta^2}{D \cdot \Phi}}, \qquad (31)$$

where the diameter of the gas cover in this area is calculated by the expression:

$$\Phi = \delta_0 \sqrt[3]{\rho_{ap} V_{gZ_3} \cdot \frac{T_g}{T_0}} \qquad (32)$$

In these circumstances the equations of the mathematical model are:

- for the variation of the temperature of the gas phase:

$$\frac{dT_g}{d\tau} = \left\{ -c_g\left(T_g - 273\right)\frac{dV_{gZ_3}}{d\tau} - \frac{6\delta^2\alpha_{gc}}{\delta_0^3\rho_{ap}}\left(T_g - T\right) - \frac{6\delta_a^2\alpha_{ga}}{\delta_0^3\rho_{ap}} \cdot \right.$$

$$\cdot\left[n_a + \frac{\left(\delta_0^3 - \delta^3\right)\rho_{ap}A^i}{\delta_a^3\rho_a}\right]\left(T_g - T_a\right) - \frac{6\delta^2}{\delta_0^3\rho_{ap}}kC_{pZ_3}\frac{T_0}{T_g} \cdot$$

$$\cdot\left[c_{O_2}\left(T_g - 273\right) - \frac{44}{32}c_{O_2}\left(T - 273\right)\right] + r_i\left(\xi + \lambda_i - 1\right)\left(T_{fl} - 273\right)c_g\frac{V_{aum}^0}{\tau_a} +$$

$$\left. + \left[\lambda_s c_{aum} t_p'' + r_{evs}\left(\xi + \lambda_{ev} - 1\right)c_g t_{ev}\right]V_{aum}^0 + \frac{6\Phi^2 a_g\sigma_o}{\delta_0^3\rho_{ap}}\left(T_{fl}^4 - T_g^4\right)\right\} / \left(c_g V_{gZ_3}\right) \quad \text{[K/s]} \qquad (33)$$

- for the variation of the temperature of the external ash, the relation 21;
- for the variation of the diameter of the coal particle which burns, the relation 22 (C_{pZ_1} is replaced by C_{pZ_3} and in the equation of the kinetic of nitrogen volatilization is introduced V_{gZ_3}).

We remark that for the values of the gas volume, for the oxygen concentration in the gas stage and for the oxygen concentration on the surface of the coke particle the relations 29, 30 and 31 are used.

The mathematical model is completed by the equations of generation of NO (thermal and from combustible) as follows:

- the equation of the kinetic of nitrogen volatilization:

$$\frac{dN^v}{d\tau} = 1500 \cdot \left(\gamma\frac{N^i}{100 \times V_{gz}} - N^v\right) \cdot e^{-\frac{4500}{T}}, \text{[kg/(}m_N^3 \cdot s\text{)]} \qquad (34)$$

- the dynamics of generation of molecular nitrogen:

$$\frac{dN_2^c}{d\tau} = 1 \cdot 10^{13} \left(\frac{N^c}{T_g} \right)^2 \cdot e^{-\frac{1000}{T_g}} \text{ [kg/(} m_N^3 \cdot s \text{)]} \tag{35}$$

- the formation speed of the nitrogen monoxide from the nitrogen from combustible:

$$\frac{dNO^c}{d\tau} = 1 \cdot 10^{11} \cdot N^c \left(\frac{C}{T_g} \right)^{1,5} \cdot e^{-\frac{3750}{T_g}}, \qquad \text{[kg/(} m_N^3 \cdot s \text{)]} \tag{36}$$

- the generation of the nitrogen monoxide from the combustion air (according to Zeldovici):

$$\frac{dNO^a}{d\tau} = 3.34 \cdot 10^{13} N_2 \left(\frac{C}{T_g} \right)^{0,5} \cdot e^{-\frac{64500}{T_g}} - 15.58 \cdot 10^{-11} \left(NO^a \right)^2 \left(C \cdot T_g \right)^{0,5} \cdot e^{-\frac{43000}{T_g}}$$

$\text{KgNO}^a/(m_N^3 \cdot s)]$ (37)

The equations system formed by the four zones has been solved (in Turbo Pascal) by the Runge – Kutta method.

Results and conclusions.

Based on the model from the area Z_0 there have been made calculation in order to determine the drying time, obviously dependent on the initial diameter of the coal particle and on x_e. For x_e=0.9 and diameters of the coal particle between 40÷160μm, the drying time alternates between 0.01÷0.030 seconds, according to Fig. 3.

The dependence of NO^c concentration on the main parameters is expressed by a relation of the form:

$NO^c_{max} = F(\delta_0, x_e, \lambda_p, \Delta\tau, r_{evp}, r_{evs})$, (38)

where r_{evp}, r_{evs} – recirculating degree of the combustion gas from the steam generator end-part which are introduced with the primary air and with the secondary air, respectively.

The system was solved using an inferior fuel (lignite) having the low heating value, Q^i_i = 7.100 kJ/kg and the concentration of the atomic nitrogen existing in fuel, N^i = 0.9 %.

In the Figs 4-6 the variation of the concentration of NO_x is presented, depending on the initial diameter of the coal particle, on the coefficient of excessive primary air and on the time interval in which the secondary air is introduced (following the linear law of time presented in the paper) for the two cases analyzed: for x_e = 1 and x_e = 0.9. The other variables interfering in the mathematical model (for example, the degree of recirculating of the combustion gases) have been kept constant for all cases taken into consideration.

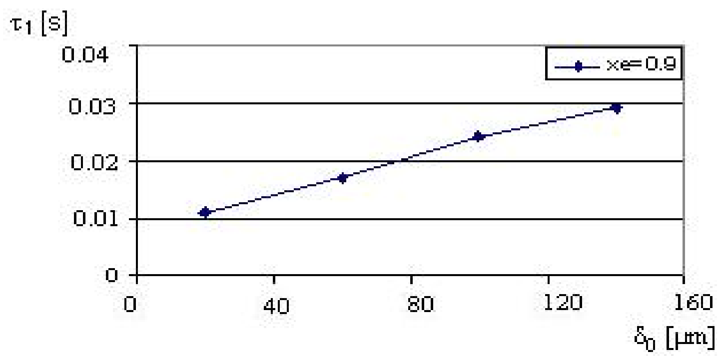

Fig.3. The variation of the drying time as function of δ_0

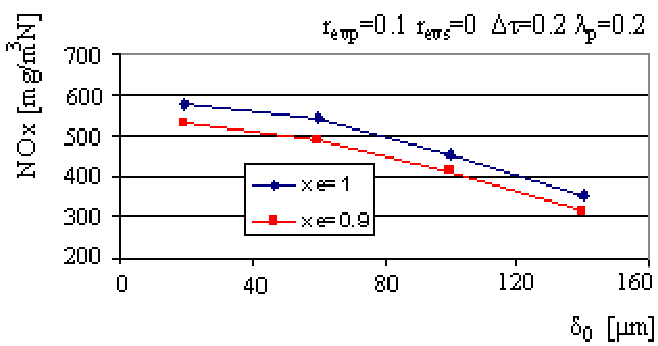

Fig.4. The variation of the concentration of NOx as function of δ_0

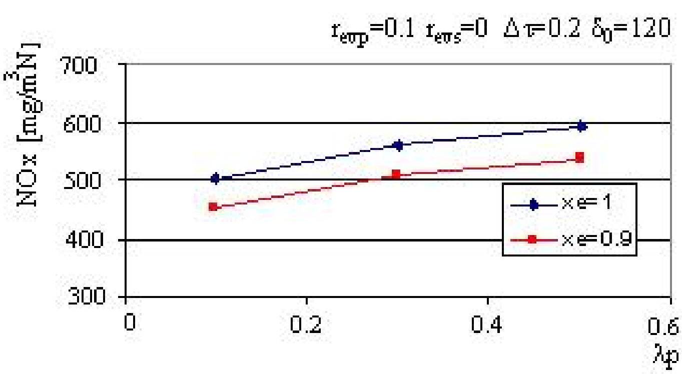

Fig. 5. The variation of the concentration of NOx as function of λ_p

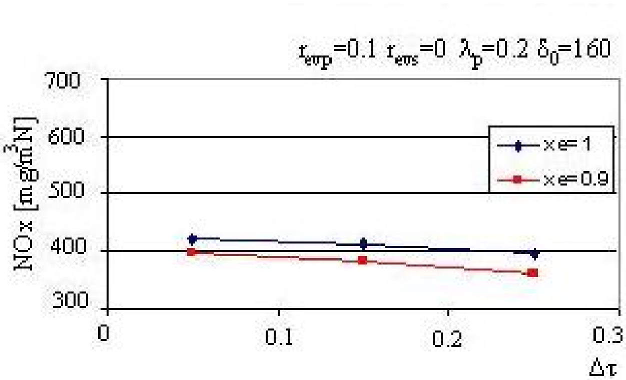

Fig.6. The variation of the concentration of NOx as function of Δ_τ

Conclusions

- In the proposed physical model the secondary air linear introduction divides the combustion time into four areas: the drying area, the ignition area, the area of combustion of volatile substance and the fourth area when the combustion process is finished;
- The secondary air introduction by an infinite number of air injections (continuous access) led to nitrogen monoxide from fuel concentration decreases up to 40-50% comparing to initial variant (air divided in two parts – primary and secondary air). If one takes into account the heterogeneous reduction of NO, in presence of residual coke (due to carbon monoxide reaction on coke basis surface) it is possible to obtain a total reduction of the nitrogen monoxide concentration greater than 60% - 80%;
- NO value diminishes when the fuel particle initial diameter increases while primary air excess coefficient decreases. It is underlined that this dynamics has a minimum NO concentration value obtained for a λ_p value which is function of initial volatiles content from coal;
- The results obtained demonstrated that the influence of the mineral mass over the nitrogen monoxide means, practically, a reducing of its total concentration, by an average, of 7-15 percents.

R E F E R E N C E S

1. *Blum,I.,Barca,Fr.,* Chimia şi prepararea combustibililor solizi. E.D.P.,Bucureşti – 1966, pp 340;
2. *Bloh, A. G., Teploobmen v topcah parovâh cotlov,* - L.;Energoatomiozdat. Leningrad otd-nie 1984, 240 st.;
3. *Neaga, C.,* Infuenţa masei minerale interne asupra dinamicii arderii particulei de cocs. Energetica, 2/1996, pp. 52-59;
4. *Isachenko, V.P. and a*., Heat Transfer (Translated from the Russian). Izd, Mir, 1977, 494 st.;
5. *Adzerikho, K. S. and a.,* Luminescence of two-phase inhomogeneous of cylindrical geometry. Int. J. Heat Mass Transfer, 1979, vol. 22, Nr.1, st. 131-136;
6. *Neaga, C., Pîşă**, I.,*** The influence of the recirculation of combustion gas over the dynamics of generation of nitrogen monoxide at the lignite burning with linear introduction of secondary air. The Energetic Review, no.1-2, pp. 27-35, Bucharest, ISSN 1220-5133, 2002;