Factors Influencing the Reburning Process in a Tangentially-Fired Pulverized Coal Furnace

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Abstract

A numerical simulation of bituminous coal reburning in a full-scale tangentially-fired boiler has been conducted with CFD method in order to study the effects of reburn zone length, the height of reburn nozzles, the stoichiometric ratio in reburn zone, the reburn fuel fraction and the reburn coal fineness on NO_x *reduction efficiency and unburned carbon in fly ash. The results indicate the largest value of* NO_x *reduction efficiency relative to the height of reburn nozzles zone; the increase of* NO_x *reduction efficiency with reburn zone length, reburn fuel fraction and the decrease of reburn coal particle size; the increase of burnout performance of coal relative to the coal particle size.*

Keywords: numerical analysis, CFD method, tangentially-fired boiler, coal reburning

Introduction

Coal combustion in the furnaces of the electric power plants being a major source of nitrogen oxides emission, techniques for reducing them have to be introduced. They can be classified into two categories: combustion control techniques and post-combustion control techniques. Combustion controls reduce NO_x formation during the combustion process, whereas post-combustion controls reduce it after the combustion process.

The first category includes low-NO_x burners, overfire air, flue gas recirculation and coal reburning – with its best version, micronized coal reburning; the second category includes selective catalytic reduction and selective noncatalytic reduction.

Coal reburning is a combustion modification consisting in three steps: ignition of the most part of coal under normal fuel-lean conditions, the injection of a reburn fuel to determine a fuel-rich zone and finally the injection of burnout air (overfire air), oxidizing hydrocarbons, carbon monoxide and hydrogen [5].

Consequently, there are three main zones in the furnace: the primary combustion zone (where coal is fired), the reburning zone (where additional fuel is added in order to create oxygen-deficient conditions for reducing the NO_x produced in the primary zone) and the burnout zone (in which overfire air is added to complete the combustion).

Tangentially-Fired Pulverized Coal Furnace Description

The main part of a tangentially-fired pulverized coal furnace is a rectangular parallelepiped having placed on each of the four vertical edges three important units: the main coal feed (actually consisting in four ports: primary air lower port, primary air upper port, secundary air lower port, secundary air upper port), the reburning coal feed/ reburning nozzle (one port) and the overfire air system (one port).

Let us denote by L the reburning zone length, i.e. the distance between the overfire air system and the reburning nozzles, and also by h the reburning nozzle height, i.e. the distance between the reburning nozzle from the upper port of the main coal feed.

Then, let D_{eq} be the equivalent (inner) diameter of the furnace, calculated as:

$$D_{eq} = \frac{4A}{P} = \frac{2Ll}{L+l} \tag{1}$$

where A stands for the cross-section area of the furnace, P stands for the cross-section perimeter and, obviously, L and l stand for the two inner dimensions of the cross-section (D_{eq} appears to be the diameter of the circle inscribable in a square having the same area as the furnace cross-section).

Now two important parameters – considered as essential in furnace geometry describing – may be defined:

The relative reburning zone length is defined as [4]:

$$L_r = \frac{L}{D_{eq}} \tag{2}$$

The relative height of reburning nozzle is defined as:

$$h_r = \frac{h}{D_{eq}} \qquad (3)$$

It is worth noticing that, in a square cross-section, the four axes of the nozzles are all tangent to an imaginary little circle; its diameter D_0 is also an input data for the calculation that is to be conducted in what follows.

Each of the three zones of a furnace presented above has a determined stoichiometric air ratio (determined by the flows of primary fuel, reburning fuel and overfire air).

This ratio is denoted as SR_1 for the primary combustion zone, SR_2 for the reburning zone and SR_3 for the burnout zone, defined as the ratio of the air used to that theoretically required for complete combustion). In what follows, SR_2 will be considered as a variable in furnace work.

As the reburn coal is injected at a rate corresponding to a certain percent of the total heat input which depends on the primary zone excess air level (the lower the primary combustion zone excess air, the lower the reburni ng coal requirement), another parameter to be specified is the reburning fuel percent, denoted as RFP.

The last variable involved in this study is pulverized coal particle size, also referring to the reburning fuel.

The reburning fuel being coal, additional handling and pulverizing equipment may have to be installed: in the furnace enters coarse crushed coal, which needs to be reduced to smaller particle sizes to be an effective reburn fuel. Pulverized coal has a particle size of approximately 60 microns. Moreover, micronized coal, which was tested as reburn fuel, with a particle size of approximately 60 microns, requires special size-reduction equipment (micro-mills)

Two indices are investigated as functions of these variables (also referred to as "work conditions"). These indices are:

- NER(%): the NO_x emission reduction, denoted as

$$NER = \frac{(NO_x)_{initial} - (NO_x)_{final}}{(NO_x)_{initial}} \cdot 100\% \qquad (4)$$

where (NO_x)initial and (NO_x)final are the nitrogen oxides emissions without and with reburning, respectively.

- the loss-on-ignition, denoted as LOI(%):

$$LOI = \frac{m_{initial} - m_{final}}{m_{initial}} \cdot 100\% \qquad (5)$$

where minitial and mfinal are the ash sample's mass without and with reburning, respectively.

By using pulverized coal as reburn fuel, up to 50% NO_x emissions reduction could be achieved in a furnace, but the ultimate purpose is minimizing loss-on-ignition whereas minimizing NO_x emissions.

It is interesting to note that micronized coal reburning can reduce not only NO_x emissions but also loss-on-ignition compared to conventional coal reburning.

Numerical Analysis

Small-scale furnaces were initially used to simulate the full-scale ones [3], experimentally investigating the effect of the height of reburning nozzles, stoichiometric ratio in reburning zone and reburning coal size on NO_x emissions reduction and on loss-on-ignition as well, in a 1MW tangentially-fired furnace.

Physical processes involved in full-scale furnaces being however not absolutely scalable, such reduced-scale experiments might be only taken into account as approximations, not to mention the very high investment and maintenance costs involved by them.

As an alternative way to simulate the full-scale furnaces, mathematical modeling provides a cost-effective powerful engineering tool in studying coal reburning.

Three-dimensional numerical simulation of coal reburning in a 29 t/h full-scale tangentially-fired furnace was conducted with CFD (Computational Fluid Dynamics), by using CHEMKIN-CFD 4.1. – a software tool for solving complex chemical kinetics problems, in order to investigate the processes of NO reduction, as a more time-efficient investigation compared to direct laboratory experiments.

The five above-mentioned variables associated with reburning system, i.e., reburn zone length, location of reburn nozzles, stoichiometric ratio in reburn zone (SR_2), reburn coal size ($\overline{d}$) and reburn fuel percent (RFP) were investigated in the simulation.

The input data were referring to the furnace and to the coal as well.

As far as the furnace is concerned, a 29 t/h utility boiler with a 4×4 m^2 section area and a 12 m height was modeled.

Its operating conditions are given in Table I.

Coal from Jiu Valley was used as both primary and reburning fuels (at six different sizes, from 10 µm to 60 µm). Its properties are given in Table II.

The boiler was modeled using a three-dimensional mesh [1].

Tab. 1. Furnace operating conditions

Tab. 1. Warunki spalania

Total coal feed rate (t/h)	6
Total air flow rate (Nm^3/h)	32500
Primary air inlet velocity (m/s)	23
Primary air temperature (°C)	365
Secondary air inlet velocity (m/s)	42
Secondary air temperature (°C)	370
Reburn air inlet velocity (m/s)	25
Reburn air temperature (°C)	368
Overfire air inlet velocity (m/s)	58
Overfire air temperature (°C)	79

Tab. 2. Coal properties

Tab. 2. Właściwości węgla

Physical properties	
Net heating value (kJ/kg)	15.53
Density (kg·m^{-3})	1200
C_p (J·kg^{-1}·k^{-1})	980
Thermal Conductivity (W·m^{-1}·K^{-1})	0.12
Swelling Coefficient	2.23
Particle Emissivity	0.93
Particle Scattering Factor	0.53
Proximate analysis (%)	
Ash A = 35,6 %	23.37
Humidity W = 11 %	37.49
Volatile = 43 %	60.51
Elemental analysis (%)	
C	82.23
H	5.47
N	1.33
O	10.27
S	0.70

To minimize the effect of the numerical pseudo-diffusion on the results obtained, a grid consistent with the flow direction and second order upwind scheme were applied in the CFD simulation.

This furnace mesh has about 230,000 nodes, being fine enough to capture all the significant influences during computation.

A CFD code was used to predict turbulence, combustion, and heat transfer in the full-scale tangentially-fired furnace [3].

Reburn Fuel Injection

Reburn fuel injection creates a reducing region within which the reburn fuel molecules break down to hydrocarbon fragments (such as CH, CH_2, CH_3) that react with NO_x, producing therefore some reduced chemical species.

Within this model, the amount of nitrogen oxide produced in combustion is characterized by the following stationary state transport equation (NO is much more important as NO_2):

$$\frac{\partial}{\partial x_i}(\rho u_i Y_{NO}) = \frac{\partial}{\partial x_i}(\rho D \frac{\partial Y_{NO}}{\partial x_i}) + S_{NO} \qquad (6)$$

Similarely, for the hydrocyanic acid:

$$\frac{\partial}{\partial x_i}(\rho u_i Y_{HCN}) = \frac{\partial}{\partial x_i}(\rho D \frac{\partial Y_{HCN}}{\partial x_i}) + S_{HCN} \qquad (7)$$

In the source term, S_{NO} in (6), contributions of thermal NO, prompt NO, fuel NO, and NO reburning are considered.

In the reburning reactions, the following three reactions are considered to be the most important reactions of NO reduction by CH_n radicals:

$$CH + NO \rightarrow \approx P : k = k_a + k_b + k_c \tag{8}$$

$$CH_2 + NO \rightarrow \approx P : k` = k_{a'} + k_{b'} + k_{c'} \tag{9}$$

$$CH_3 + NO \rightarrow \approx P : k'' = k_{a''} + k_{b''} \tag{10}$$

or, more specifically,

$$\begin{aligned} CH + NO &\rightleftharpoons HCN + O : k_a = 5.0 \cdot 10^{13} \\ &\rightleftharpoons NCO + H : k_b = 2.9 \cdot 10^{13} \\ &\rightleftharpoons HCO + N : k_c = 2.9 \cdot 10^{13} \end{aligned}$$

$$\begin{aligned} CH_2 + NO &\rightleftharpoons HCN + OH : k_{a'} = 2.9 \cdot 10^{14} T^{-0.69} e^{-760/RT} \\ &\rightleftharpoons HNCO + H : k_{b'} = 3.1 \cdot 10^{17} T^{-1.38} e^{-1270/RT} \\ &\rightleftharpoons HCNO + H : k_{c'} = 3.8 \cdot 10^{13} T^{-0.36} e^{-580/RT} \end{aligned}$$

$$\begin{aligned} CH_3 + NO &\rightleftharpoons H_2O + HCN : k_{a''} = 9.6 \cdot 10^{13} e^{-28800/RT} \\ &\rightleftharpoons H_2CN + OH : k_{b''} = 1.0 \cdot 10^{12} e^{-21750/RT} \end{aligned}$$

The global NO reduction rates for reaction pathways can be expressed as:

$$\frac{d[NO]}{dt} = -k[CH][NO] - k'[CH_2][NO] - k''[CH_3][NO]$$

where k, k' and k" are the rate constants for the reactions (8), (9) and (10), respectively.

In this study, the rate constants k, k' and k" are expressed in $m^3/(mol \cdot s)$.

The source terms for (6) and (7) due to reburning reactions are given by [2]:

$$S_{reburning,NO} = M_{NO} \frac{d[NO]}{dt} \tag{11}$$

$$S_{reburning,HCN} = M_{HCN} \frac{d[HCN]}{dt} = -M_{HCN} \frac{d[NO]}{dt} \tag{12}$$

Results and Discussion

Effects of the reburn zone length on both NER and LOI.

In the reburning simulations, primary fuel was the conventional coal and the stoichiometric ratio in primary combustion zone and reburn zone were 1.1 and 0.9, respectively. The overall stoichiometric ratio at the exit of furnace was 1.2, the relative height of reburn nozzles remained 0.280, and RFP was 20%.

In the next six figures, the thick line means d=50 microns, the mean line means d=30 microns, whereas the thin line means d=20 microns. In the last two figures, the thick line means RFP=30%, the mean line means RFP=20%, whereas the thin line means RFP=10%.

What is worth mentioning is that LOI being less than 1 means that the unburned carbon level in fly ash is lower than that of baseline; for this reason, the curve LOI=1 is shown in the Figures 2, 4, 6 and 8.

Influence of the Relative Reburn Zone Length on NER and LOI

Figures 1 and 2 illustrate NER and LOI at different reburn coal sizes, as functions of relative reburn zone length.

Both NER and LOI at different reburn coal sizes show similar trends in these figures.

The results indicate the relationship between the reburn zone length and NER is almost linear.

With the increase of relative reburn zone length, NER increases slightly, but LOI increases noticeably.

When OFA ports are too close to reburn nozzles for a fixed height of furnace (that is, reburn zone length is too small), flue gas residence time in reburn zone is too short, and then NO_x reduction reactions are not completed in the reburn zone.

Therefore, the increase of reburn zone length can obtain high values for NER.

However, when OFA ports are too far from reburn nozzles for a fixed height of furnace (that is, reburn zone length is too great), flue gas residence time in burnout zone is too short so as to decrease coal particle burnout ratio.

Influence of the Height of Reburn Nozzles on NER and LOI

The relative reburn zone length remained 0.187, and the locations of reburn nozzles were changed to investigate the influence of height of reburn nozzles on NER and LOI. The numerical results are shown in Figures 3 and 4.

It is clear that both NER and LOI at different reburn coal sizes show similar trends in Figures 3 and 4.

NER at height of reburn nozzles 0.210 indicates that the height of reburn nozzles has optimum value where NO_x reduction efficiency is the highest. When reburn nozzles are too close with upper primary air for a fixed height of furnace (that is, h0 is too small), air in primary combustion zone enters reburn zone earlier so as to weaken the reducing atmosphere in reburn zone, and then the hydrocarbon radicals provided by reburn coal during the process of coal pyrolysis in reburn zone are easy oxidized and form NO_x rather than to reduce NO_x.

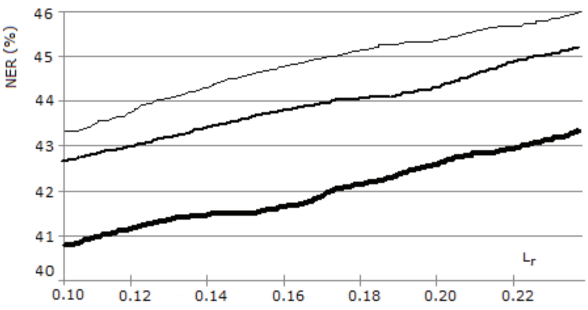

Fig. 1. Influence of the reburn zone length on NER

Rys. 1. Wpływ wielkości strefy dopalania na NER

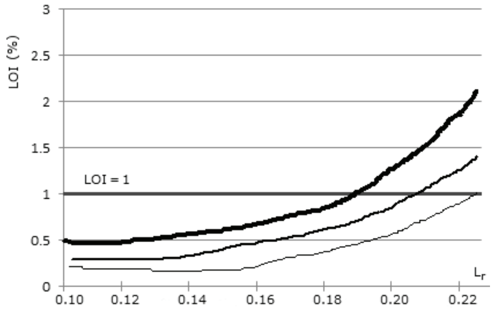

Fig. 2. Influence of the reburn zone length on LOI

Rys. 2. Wpływ wielkości strefy dopalania na LOI (straty prażenia)

However, when reburn nozzles are too far from upper primary air (that is, h0 is too great), reburn fuel far away partial high temperature region in furnace so as to weaken the NO_x reduction reactions, and the flue gas residence time in oxidizing atmosphere is too long, and then the NO_x emissions increase. Therefore, for a fixed distance from upper primary air, there is an optimum location of reburn nozzles for NO_x reduction which can ensure the reburn coal does not mix early with air of primary combustion zone to keep reducing atmosphere and can ensure enough high temperature to make NO_x reduction reactions fierce in reburn zone and can ensure reasonable flue gas residence time to make NO_x emissions decreased in oxidizing atmosphere.

With the increase of the relative height of reburn nozzles at a fixed dm, the increase of NER is accompanied by the slight increase of LOI when the relative height is less than 0.210, but the decrease of NER is accompanied by the continuous slight increase of unburned carbon in fly ash when the relative height is greater than 0.210, as shown in Figures 3 and 4.

Influence of the Stoichiometric Ratio in Reburn Zone on NER And LOI

In the coal reburning simulations, the relative reburn zone length remained 0.187, and the relative height of reburn nozzles remained 0.210. Figures 5 and 6 illustrate NER and LOI at three different reburn coal particle sizes, d=20, 30 and 50 microns, as functions of stoichiometric ratio in reburn zone SR_2. Both NER and LOI at different reburn coal sizes show similar trends in these figures.

With the decrease of the stoichiometric ratio in reburn zone at a fixed diameter, the increase of NOx reduction efficiency is accompanied by the increase of unburned carbon in fly ash when SR_2 is greater than 0.9, but the decrease of NER is accompanied by the continuous noticeable increase of LOI when SR_2 is less than 0.9, as shown in Figures 5 and 6.

Influence of the reburn fuel fraction and the reburn coal fineness on NER and LOI

Since particle-size of coal can affect combustion property, this can affect NO_x reduction efficiency and unburned carbon in fly ash when different particle-size coals are utilized as reburn fuel. Based on the above studies, coals with different size injected at same position were investigated. Three reburn fuel fractions (RFP=10%, 20% and 30%) were investigated.

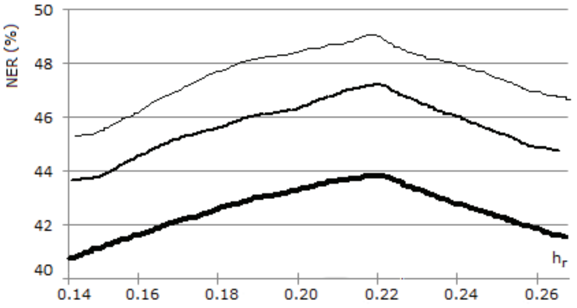

Fig. 3. Influence of height of reburn nozzles on NER

Rys. 3. Wpływ wielkości dyszy na NER

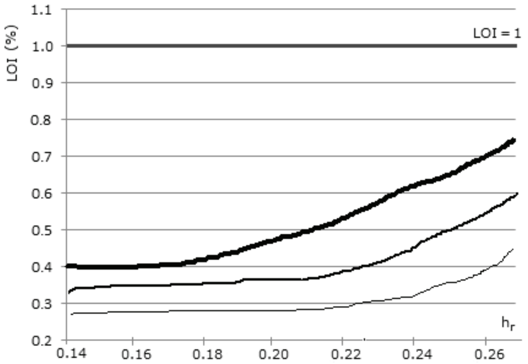

Fig. 4. Influence of height of reburn nozzles on LOI

Rys. 4. Wpływ wielkości dyszy na LOI

Fig. 5. Influence of stoichiometric ratio in reburn zone on NER

Rys. 5. Wpływ stosunku stechiometrycznego w strefie dopalania na NER

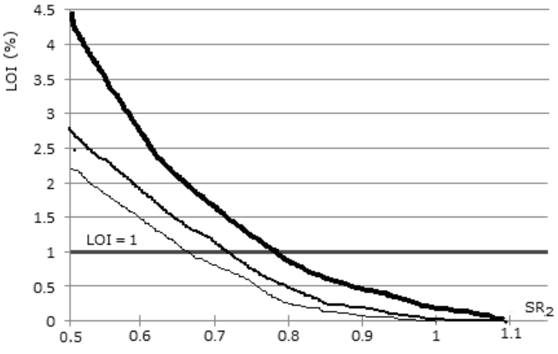

Fig. 6. Influence of stoichiometric ratio in reburn zone on LOI

Rys. 6. Wpływ stosunku stechiometrycznego w strefie dopalania LOI

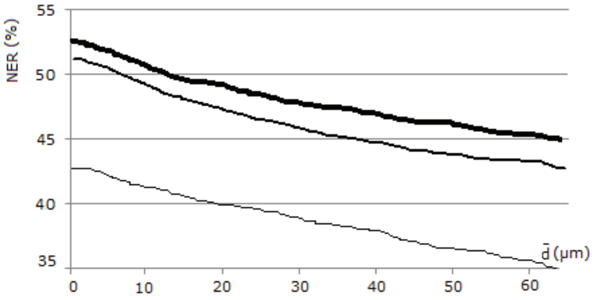

Fig. 7. Influence of reburn fuel fraction and particles' fineness on NER

Rys. 7. Wpływ udziału paliwa i uziarnina na NER

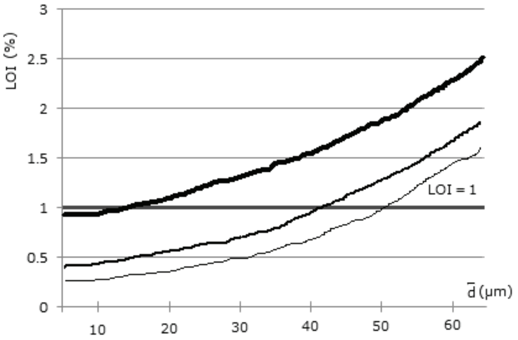

Fig. 8. Influence of reburn fuel fraction and particles' fineness on LOI

Rys. 8. Wpływ udziału paliwa i uziarnina na LOI

In the coal reburning simulations, stoichiometric ratio in reburn zone remained 0.8, the relative reburn zone length remained 0.187, and the relative height of reburn nozzles remained 0.210.

Figures 7 and 8 illustrate NER and LOI at different reburn fuel fractions, as a function of reburn coal particle size dm. Both NER and LOI at different reburn fuel fractions show similar trends inthese figures.

For a fixed reburn coal size, NO_x reduction efficiency increases with increasing reburn fuel fraction below 20%, and NER increases slightly as reburn fuel fraction further increases.

With the increase of reburn fuel fraction, relative unburned carbon in fly ash increases.

The relationship between reburn coal size and NER is almost linear. NER increases noticeably with the decrease of reburn coal size. With the decrease of the coal size, the entire reactive surface is enlarged, and the diffusive resistance also decreases.

Therefore, the total of burnout rate will increase significantly, and LOI will decrease noticeably, as shown above.

Conclusion

The study proved that the decrease of reburn pulverized coal size can obtain high combustion efficiency and high NOx reduction efficiency.

However, getting finer particles requires additional power consumption in coal pulverized operation. Above all, the choice of the reburn coal particle size should take into account the above factors.

Literatura – References

1. Canning, P. J., Hill R., Powergen U. K.: Development of coal-on coal, DTI/Pub URN 02/900, 1–7, (2002).
2. Maly, P. M., Zamansky, V. M., Ho L., Payne R.: Alternative fuel reburning, .Fuel, 78(3), 2006
3. Smoot, L. D., Hill, S H.: NOx control through coal reburning, Prog. Energ. Combust. Sci., 24 (5), 2008.
4. www. netl.doe.gov
5. Xu, H., Smoot, L. D., Tree, D. R.: Prediction of nitric oxide destruction by advanced reburning, Energy & Fuels, 15, 541–551, (2001)

Czynniki wpływające na proces dopalania w kotle zasilanym stycznie pyłem węglowym piecu

Numeryczna symulacja dopalania węgla kamiennego w pełnej skali, w kotle zasilanym stycznie zostało przeprowadzone metodą CFD. Celem było zbadanie wpływu długości strefy dopalania, wysokość dysz do dopalania, stosunku stechiometrycznego węgla i powietrza, rozdrobnienia węgla na efektywność redukcji NOx i niedopału węgla w popiele lotnym. Uzyskane wyniki wskazują że największy wpływ na sprawność redukcji NOx ma wysokości dysz i zmniejszenie rozmiarów cząstek węgla.

Słowa kluczowe: analiza numeryczna, modelowanie CFD, kocioł zasilany stycznie, dopalanie węgla