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Professional paper

PREDICTION OF NO_X EMISSIONS FOR FBC BOILERS BY EMPIRICAL MODELS – THE INFLUENCE OF SCALE-UP

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Reliable prediction of NO_X emissions can provide useful information for boiler design and fuel selection. The disadvantages and complexity of recently used kinetic NO_X prediction models could be overcome by developing a simple empirical model. However, existing empirical models for prediction of NO_X are used exclusively for pulverized coal boilers. This paper aims to modify some commonly used pulverized coal combustion empirical NO_X prediction models – Pohl´s model and Ibler´s model – to fit the fluidized bed combustion boilers. The data from large scale fluidized bed combustion units are used for empirical models modification and compared with the data from pilot scale 0.5 MW fluidized bed combustion boiler. The reliability of proposed modifications to physical models and the influence of scale-up are discussed. The maximum reliability was achieved by modified Ibler´s model. If fuel mixtures were excluded the reliability increased. The NO_X emissions of pilot scale boiler were higher compared to large scale units. However, these values were in agreement with Ibler´s model prediction, meaning the cause of higher values are fuel and combustion parameters and not the scale-up.

Key words: NO_X prediction, fluidized bed, empirical models.

Predviđanje emisija NO_X za FBC kotlove pomoću empirijskih modela – Utjecaj promjene veličine. Pouzdano predviđanje emisija NO_X može osigurati korisne informacije za dizajn kotla i izbor goriva. Nedostaci i složenost nedavno korištenih kinetičkih modela predviđanja NO_X mogu se prevladati razvojem jednostavnog empirijskog modela. Međutim, postojeći empirijski modeli za predviđanje NO_X koriste se isključivo za kotlove na ugljen u prahu. Ovaj rad ima za cilj promijeniti neke najčešće korištene empirijske modele predviđanja NO_X za izgaranje ugljena – Pohlov i Iblerov model – kako bi odgovarali izgaranju u fluidiziranom sloju kotlova. Podaci stvarnog izgaranja u fluidiziranom sloju korišteni su za modificirane empirijske modele i uspoređeni s vrijednostima izgaranja u fluidiziranom sloju kotla pilot scale postrojenja od 0,5 MW. Komentirani su pouzdanost predložene modifikacije fizičkog modela i utjecaj promjene veličine. Maksimalna pouzdanost postignuta je modificiranim Iblerovim modelom. Pouzdanost se povećava ako isključimo smjesu goriva. Emisije NO_X pilot scale kotla su veće u odnosu na stvarne jedinice. Međutim, te vrijednosti su u skladu s Iblerovim model predviđanja, što znači da veće vrijednosti uzrokuju gorivo i parametri izgaranja, a ne faktor promjene veličine.

Ključne riječi: predviđanje NO_X, fluidizirani sloj, empirijski modeli.

INTRODUCTION

Prediction of NO_X emissions can be very useful not only in the design phase of a new boiler but also for existing boilers. When the fuel change is necessary for an existing boiler the knowledge of expected NO_X emissions can lead to selecting an optimal fuel and evaluate whether/what kind of secondary denitrification technology will be needed to abide emission limit.

The complexity of phenomena taking place in a fluidized bed makes reliable prediction of NO_X quite difficult. The common approach is kinetic modelling combined with the hydrodynamic model of a fluidized bed and freeboard. However, these models tend to be far too complex. To respect all occurring processes hundreds of reversible chemical reactions must be included in the kinetic model. Moreover, the hydrodynamic model of the fluidized bed must be divided into many control volumes to respect different flow patterns in different parts of bed. These arrangements increase complexity of the models over acceptable limits.

Empirical modelling approach uses simple correlations for NO_X prediction without the need for extensive computation capacity. However, existing empirical models for NO_X prediction are used exclusively for PCC boilers. The only reference available for modification of this method for FBC boilers is [1]. This paper broadens up the data previously published in [1] by adding measurements from another large scale FBC boiler at the CHPP Poříčí and also includes the data measured on the pilot scale FBC boiler on the premises of CTU in Prague.

EMPIRICAL MODELS USED

Empirical modelling approach uses the dependency of NO_X emissions on influencing parameters (fuel, boiler design or boiler operation) to form simple prediction correlations. The downfall of this method is the uncertainty caused by incomplete input data resulting in limited applicability of empirical models. See [1] or [2] for more detailed information on empirical models.

Pohl's model

Simple physical correlation have been developed by Pohl et al. [2] to estimate NO emissions for controlled mixing conditions (different types of PCC flames), see equation (1) and Table 1. Where NO_{eq} [ppm] is maximum emission of NO provided all fuel nitrogen converts to NO, N^{daf} [%] is nitrogen content in combustible, VM [%] is combustible volatile matter and FC [%] is fixed carbon content. NO_{eq} can be calculated from nitrogen content and dry flue gas volume V_{fd} [m_n^3/kg], ash content A^r [-] and water content W^r [-], using equation (2). Presumably, different set of constants will be needed for FBC conditions.

Later, Pohl added a correction of his model on the oxygen concentration in the combustion zone, see equation (3).

Pohl´s model was constructed on basis of a wide range of experimental data from PCC boilers (diffusion flame) [2-5].

$$NO[ppm] = k_1 + k_2 \cdot \frac{N^{daf}}{1,5} + k_3 \cdot \frac{VM}{40} \cdot \frac{NO_{eq}}{3200} + k_4 \cdot \frac{FC}{60} \cdot \frac{NO_{eq}}{3200} \qquad (1)$$

$$NO_{eq}[ppm] = \frac{2,1422 \cdot N^{daf} \cdot (1 - A^r - W^r)}{V_{fd}} \cdot 10^6 \qquad (2)$$

$$NO^*[ppm] = NO \cdot (0,6 + 0,135 \cdot O_2) \qquad (3)$$

Table 1. Pohl´s correlation coefficients for PCC boilers
Slika 1. Pouzdanost predviđanja NO_X korištenjem originalnog Pohlovog modela

	Premixed flame	Diffusion flame	Staged combustion
k_1	285	340	150
k_2	1280	835	80
k_3	180	20	-30
k_4	-840	-395	100

Ibler's model

Ibler et al. [6] proposed the correlation (4) for prediction of fuel nitrogen conversion to NO. Where K [-] is fuel related constant (Ibler recommended using values of constant K between 4 and 6 for Czech coals), C_{O2} [%] is flue gas oxygen concentration and T [K] is combustion temperature. The predicted concentration in ppm can be calculated by multiplying the fuel nitrogen conversion with NO_{eq} from equation (2).

$$\frac{NO}{NO_{MAX}}[\text{-}] = 7 \cdot 10^{-5} \cdot \mathrm{K} \cdot \mathrm{C}_{\mathrm{O_2}}{}^{2} \cdot \sqrt[3]{(\mathrm{T} - 1025)} \qquad (4)$$

The constant $7 \cdot 10^{-5}$ in the equation (4) represents the PCC conditions and a presumably different constant will be needed for FBC conditions. As can be seen from equation (3), Ibler's model is targeted more on combustion conditions than fuel properties, which are characterized by a constant K only.

EXPERIMENTAL

The main aim of this paper is to evaluate the measured data of NO_X emissions from large scale FBC boilers situated in CHPP at Komořany, Mladá Boleslav, Poříčí and the data measured in the laboratory of CTU in Prague on a pilot scale FBC boiler "Golem". Measured data are compared with prediction of Pohl´s and Ibler´s model.

The summary of boiler parameters and combustion conditions is shown in Table 2. The steam values for the CTU in Prague pilot scale unit "Golem" are not available since the boiler does not produce any steam or useful energy and all heat is removed by a water cooling cycle.

Table 2. Boiler parameters
Tablica 2. Parametri kotla

	Komořany	Mladá Boleslav	Poříčí	Golem
Steam output [t/h]	125	140	250	See text
Steam temperature [°C]	490	535	520	See text
Steam pressure [MPa]	7,3	12,5	10	See text
Oxygen after ECO [%]	3.8 – 4.7	4 - 5	3.3 – 6.3	8 – 12.4
Bed temperature [°C]	815 - 866	873	850	800 - 850
Fuel mixture [mass%] LC/B/HC	100/0/0	40 – 85/0 – 25/0 - 50	8 – 100/0 – 92/0	100/0/0

The FBC boiler K3 with bubbling bed from combined power plant Komořany I was used as a first reference. Lower part of the combustion chamber containing the bed is lined and contains in – bed evaporator. The upper part contains wall and grid parts of the evaporator. Convection part, that follows the combustion chamber, contains superheaters (primary, secondary and output) and economizer. Tube – type air heater with a separate part for fluidization and secondary air is the last heat transfer surface of the boiler. The boiler is equipped with bed material recirculation system as well as bed height control. Combustion process is controlled by fluidization air flow rate and fuel input. The steam quality is adjusted by feed water injection before the last superheater. See more details in [1].

The FBC boiler K90 with circulating bed from Mladá Boleslav combined heat and power plant was used as the second reference. The boiler is designed for hard coal combustion, however the recent fuel is a mixture of hard and lignite coal with addition of biomass. The combustion chamber with lined lower part contains the membrane-wall type evaporator. After the combustion chamber a cyclone for coarse particle separation follows. The second duct containing membrane-wall, tube and wall type superheaters and economizer followed by hopper. The third duct contains the tube-type air heater, which is the last heat transfer surface of the boiler. The steam quality is controlled by feed water injection before the second and last superheater.

The boiler from Poříčí CHPP is a circulating FBC boiler with natural water circulation and a single drum. The combustion chamber walls constitute a membrane wall evaporator. The lower part of the combustion chamber is protected by lining (4.7 m). Walls also contain secondary air input nozzles and limestone chutes. The second tract contains three convection superheaters regulated by feed water injection.

The boiler “Golem”, situated on the premises of CTU in Prague, is a bubbling FBC boiler with thermal power output ca. 500 kW. The first pass is lined and has water cooled double wall on the outer side. Combustion chamber can be considered adiabatic due to very low heat removal. The secondary pass is equipped with fire tube heat exchanger. Fluidization air is supplied by primary air fan with controllable frequency. Primary air is introduced via a V-shaped trough type distributor, equipped with 36 nozzles, at the bottom of the primary pass. Secondary air is supplied by separate fan and distributed at 4 height levels. At each level 4 entry points are situated on the circumference of the primary tract. Each of these 16 entry points is equipped with a control flap. The boiler allows flue gas recirculation from the cyclone exit to the primary air duct. Fuel is introduced to the boiler by a screw conveyor, the entry point is on the bed surface at the wall.

Fuel

The summary of fuel parameters is shown in Table 3. Fuels combusted are lignite coal (LC), hard coal (HC) and biomass (B), respectively their mixtures. The subscripts in Table 3 represents boiler in which the fuel is combusted.

Komořany CHPP is combusting lignite coal (LC_K) only. Mladá Boleslav CHPP is combusting a mixture of hard (HC_{MB}) and lignite coal (LC_{MB}) with addition of biomass (B_{MB}) pellets. Poříčí CHPP is combusting a mixture of lignite coal (LC_P) with biomass (B_P) - wood chips. The combustion tests of the pilot plant boiler Golem were conducted with two types of lignite coal (LC_G and LC_{G2}).

Table 3. Fuel parameters
Tablica 3. Parametri goriva

	LC_K	HC_{MB}	LC_{MB}	B_{MB}	LC_P	B_P	LC_G	LC_{G2}
LHV [MJ/kg]	13	24.3	18.8	15.2	17	9	10.1	10.1
W^r[%]	28	13.2	28.2	13.7	28.5	45	30	43.6
A^r[%]	15	11.7	6.4	4.5	11	2	28	13.3
N^{daf}[%]	1	0.9	1.4	1.9	0.5	0.2	1.3	0.8

RESULTS

Experimental data were mostly taken from other author´s reports on measurements performed at CHPP Komořany, Mladá Boleslav and Poříčí [7-9]. Data from the CTU in Prague pilot scale boiler were measured by authors. During all measurements the boiler load was in the range of 75 – 100 % and the CO concentration between 80 – 220 ppm.

Pohl's model results

As a basis for NO_X prediction by Pohl´s model for FBC boilers coefficients for staged combustion model were adopted. Furthermore, three options were explored. At first the original Pohl´s model as was proposed by equation (1) was used. As was expected the reliability was very low, see Figure 1. The prediction is almost constant and independent on the actual measured value

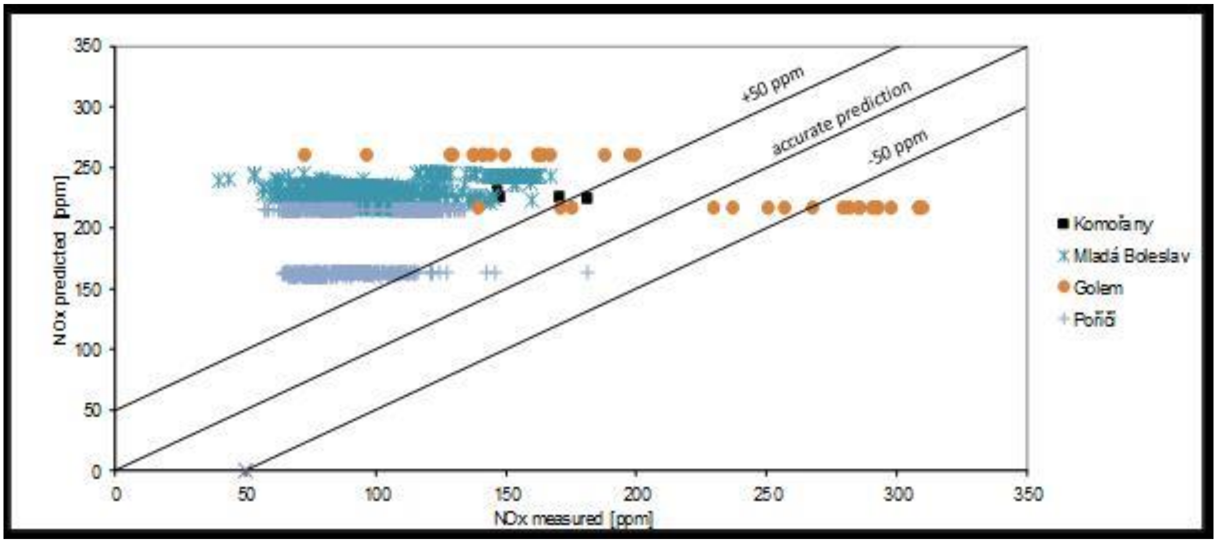

Figure 1. NO_X prediction reliability by original Pohl´s model
Slika 1. Pouzdanost predviđanja NO_X korištenjem originalnog Pohlovog modela

As the second option the modification from equation (3) was used to compensate the influence of oxygen concentration and the coefficient k_1 was optimized by least square method for better fit with the x = y line. The best fit with determination index $R^2 = 10.9$ % was found for $k_1 = 19.69$, see Figure 2. As can be seen the reliability is still very low.

The third option incorporated the temperature and excess oxygen dependency proposed by Ibler into the coefficient k_1, see equation (5). The modified constant k_1 was optimized by least square method for the best fit with the x = y line, see Figure 3.

$$k_1 = 0,25 \cdot C_{O2}^2 \cdot \sqrt[3]{T - 1025} \qquad (5)$$

Modified version of Pohl´s method showed better results, however, determination index and the prediction reliability is still very low $R^2 = 18.54\%$. It can be observed that the prediction trend for large scale boilers is virtually non-existent, however, in case of Golem a relatively good trend was measured. This effect could be caused by a fact that the combustion parameters of large scale boilers are quite stable while the parameters of Golem were varied a lot during measurement. Also, the measure-ments on Golem form two discreet groups which represent two different types of lignite coal.

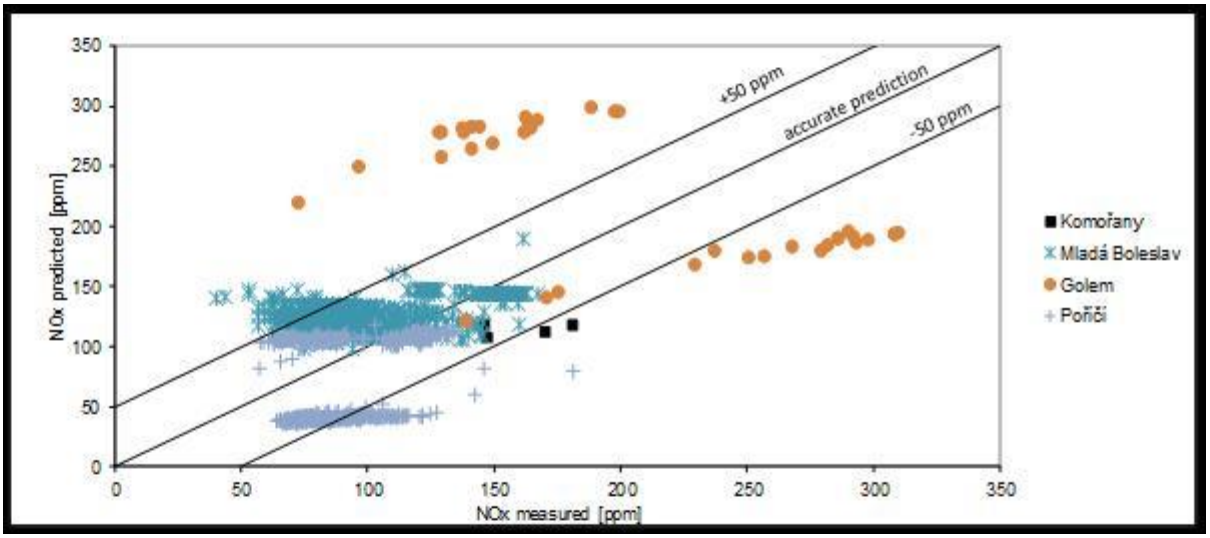

Figure 2. NO_X prediction reliability by Pohl´s model with compensation for oxygen concentration
Slika 2. Pouzdanost predviđanja NO_X korištenjem Pohlovog modela s kompenzacijom za koncentraciju kisika

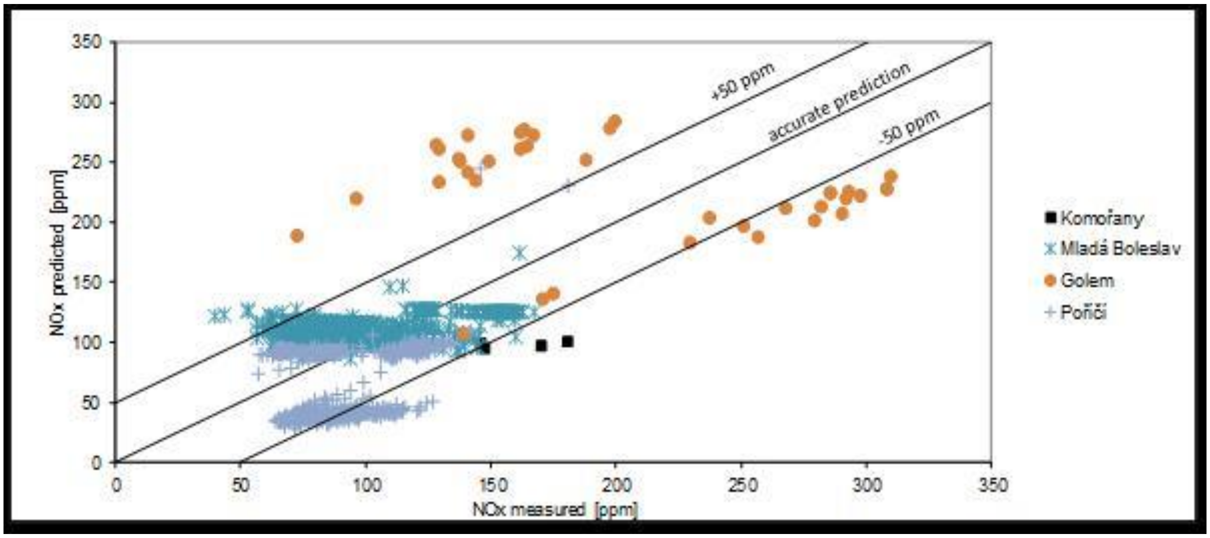

Figure 3. NO_X prediction reliability by Pohl´s model with modified constant k_1
Slika 3. Pouzdanost predviđanja NO_X korištenjem Pohlovog modela s modificiranom konstantom k_1

Ibler’s model results

Results of original Ibler´s model predictions were not in a good agreement with measured data, see Figure 4. To increase the reliability the combustion constant was modified from $7\cdot10^{-5}$ to $2.91\cdot10^{-4}$ and fuel constants K were optimised to values presented inTable 4 both by least square method fitting the x = y line. See the results in Figure 5 with R^2 = 60.86 %.

Table 4. Values of fuel constant K
Tablica 4. Vrijednosti konstante K za gorivo

	LC_K	HC_{MB}	LC_{MB}	B_{MB}	LC_P	B_P	LC_G	LC_{G2}
K [-]	**6.35**	**4.51**	**2.84**	**-3.01**	**1.41**	**3.34**	**0.53**	**1.90**

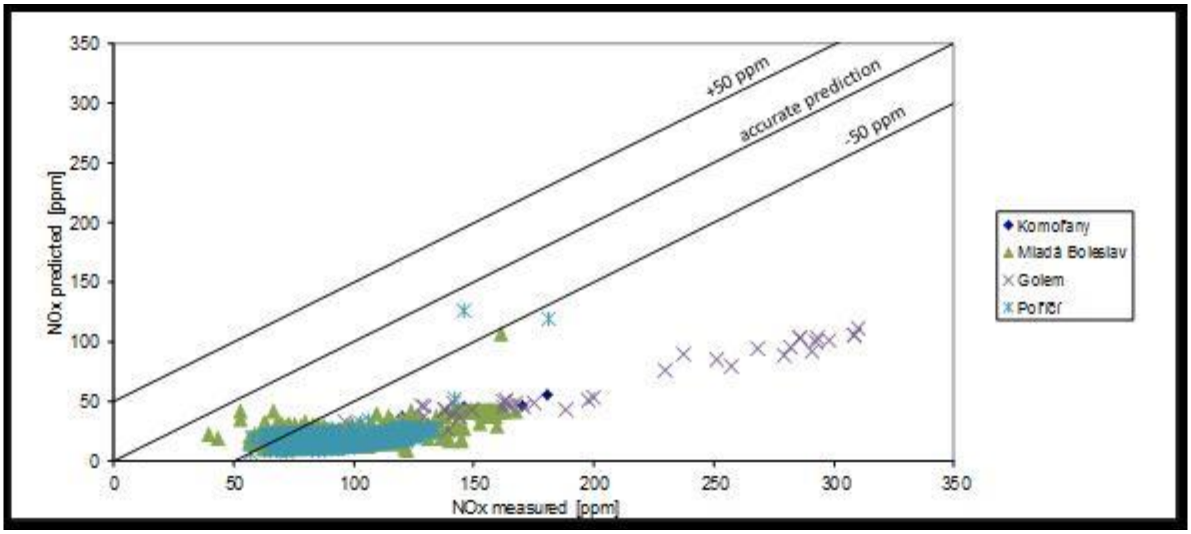

Figure 4. NO_X prediction reliability by Ibler´s model
Slika 4. Pouzdanost predviđanja NO_X korištenjem Iblerovog modela

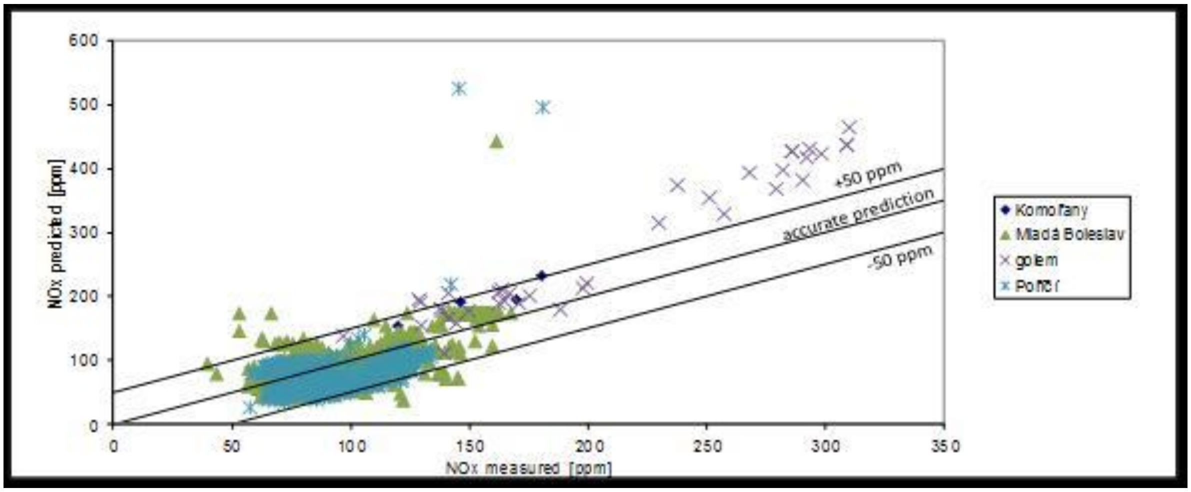

Figure 5. NO_X prediction reliability by Ibler´s model with optimized constants
Slika 5. Pouzdanost predviđanja NO_X korištenjem Iblerovog modela s optimiziranim konstantama

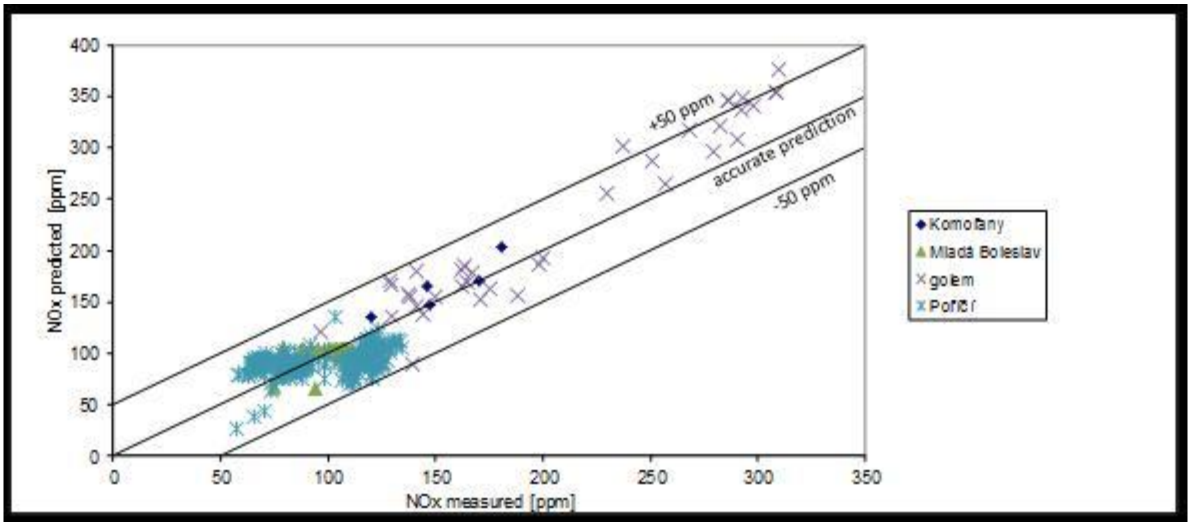

Figure 6. NO_X prediction reliability by Ibler´s model with optimized constants (only for single fuel combustion)
Slika 6. Pouzdanost predviđanja NO_X korištenjem Iblerovog modela s optimiziranim konstantama (samo za izgaranje pojedinog goriva)

Moreover, an interesting fact was observed for Iblers´s model. Most of the points that are not in agreement with the prediction are fuel mixtures. If all fuel mixtures are excluded from the prediction and only single fuel combustion is considered the determination index rises to $R^2 = 81.36$ %. With the combustion constant $2.9 \cdot 10^{-4}$ and fuel constant K from Table 5 both optimized by least square methodfitting the x = y line. This may be caused by different conversion factor of fuel N to NO_X for coal and biomass. It is also an interresting fact that the biomass combusted in Mladá Boleslav (pellets) has negative fuel constant value while the one combusted at Poříčí (wood chips) has possitive.

Table 5. Values of fuel constant K (only for single fuel combustion)
Table 5. Vrijednosti konstante K za gorivo (samo za izgaranje pojedinog goriva)

	LC_K	LC_{MB}	LC_P	LC_G	LC_{G2}
K [-]	5.55	2.8	1.43	0.47	1.55

CONCLUSION

This article aims to modify empirical NO_X prediction models, used for PCC boilers, to the FBC combustion conditions. This modification is problematic because the

NO_X formation mechanisms in PCC and FBC boilers are different. At FBC boilers the thermal formation mechanism is negligible thanks to low combustion temperature and most of the NO_X originates from the fuel. However, these model modifications are first step in a new model development.

For NO_X prediction Pohl´s and Ibler´s model were used. Measurement data from CHPP Komořany, Mladá Boleslav, Poříčí as well as pilot scale unit "Golem" on the premises of CTU in Prague were used.

In the previously published article [1] using the data of only 2 units both models showed relatively good reliability after optimization of constants with Ibler´s model being slightly better. By adding more measuremens the reliability decreased for both models. Pohl´s model now seems completely unfit for FBC prediction with maximum achieved determination index R^2 = 18.54 % after optimization.

Ibler´s model after optimization shows relatively good agreement of measured and predicted data with determination index R^2 = 60.86 %. The optimized combustion constant is $2.91 \cdot 10^{-4}$ and fuel constants K are presented in Table 4.

It was observed that fuel mixtures tend to differ from the model predictions. If a single fuel combustion is taken separately the Ibler´s model can be optimized with much higher determination index R^2 = 81.36 %.The optimized combustion constant is $2.9 \cdot 10^{-4}$ and fuel constant K are presented in Table 5.

The effect of a scale-up was not observed in the range pilot scale and large scale units. The NO_X emissions of the pilot scale unit is predicted by Ibler´s model and is likely to be caused by fuel properties and combustion conditions.

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