Dynamic model of NOx emission for a fluidized bed sludge combustor

S. Li[1], C. Cadet[1], P.X. Thivel[2], F. Delpech[2]

[1]GIPSA-lab, Dep Automatique, UMR 5216 CNRS-INPG-UJF
BP46, 38402 Saint Martin d'Heres Cedex, France (tel. +33(0)476826412,
e-mail: shi.li@lagep.univ-lyon1.fr, catherine.cadet@gipsa-lab.inpg.fr
[2]LEPMI, UMR 5631 CNRS-INPG-UJF
BP 76, 38402 38402 Saint Martin d'Heres Cedex (tel. +33(0)476826733,
e-mail: pierre-xavier.thivel@ujf-grenoble.fr, francoise.delpech@ujf-grenoble.fr

Abstract: Sludge incineration in fluidized bed is a very complex process, producing gaseous pollutants (carbon monoxide (CO) and nitrogen oxides (NOx)). The legislative norms need to be respected in spite of variations of sludge in composition and in quantity. The NOx formation, due to lots of chemical reactions from sludge nitrogen, is partly unknown. This paper deals with the design of a dynamic model of NOx emissions for a fluidized bed sludge combustor to be used in control strategy. The model is validated with industrial data, and the simulation results validate the simplification hypotheses, but need the reconstruction of sludge composition.

Keywords: sludge incineration, fluidized bed, NOx, chemical reaction, modelling, validation.

1. INTRODUCTION

The treatment and disposal of sewage sludge is an expensive and environmentally sensitive problem. It is also a growing worldwide problem since sludge production will continue to increase and since environmental quality standards become more stringent. Compared with landfill and agricultural compost, incineration presents some advantages: large volume reduction, stabilized ash production (heavy metals included) and toxic organic matters destruction. However to be economically viable, sludge has to be burned without fuel supply locally in wastewater treatment plant (Reimann, 1999).

Fluidized bed combustors are industrially largely used for coal, wastes and sewage sludge combustion (Werther and Ogada, 1999). The incineration process produces gaseous pollutants, mainly carbon monoxide (CO) and nitrogen oxides (NOx), which have to respect the legislative norms. Carbon monoxide formation can be limited by oxygen supply regulation, which is widely used in industrial plants. However, nitrogen oxides emissions should be controlled during combustion because its post-treatments are rather expensive. Linear dynamic models of coal combustion to be used in control strategy (Muir et al., 1997), (Bittanti et al., 2000) (Ikonen and Kortela, 1994), have showed that the combustion process presents a highly non linear behaviour, which needs a control strategy based on nonlinear models. Therefore, a suitable model has to be developed.

Models of coal combustion for simulation purpose (Gogebakan and Selçuk, 2004), (Huilin et al., 2000), (Adanez et al., 2001), and models of other fuels, as waste combustion (Marias et al., 2001), are based on accurate considerations on combustor hydrodynamics, which are highly complex and lead to models that do not fit to be used in control strategy. In addition, most of them target combustion efficiency without considering pollutant formation.

The sludge thermal decomposition in fluidized bed is based on the reference (Werther et Ogada, 1999). The NOx formation and reduction, due to lots of chemical reactions from sludge nitrogen, are partly unknown. Only one model, dedicated to biomass combustion (Liu and Gibbs, 2002), includes many chemical reactions of NOx formation and reduction, and will be our reference for reaction scheme. The proposed model is based on the molar and energy conservation balances, and is validated with industrial data.

2. MODEL DEVELOPMENT

2.1 Sludge thermal decomposition

A typical sludge analysis is shown in Table 1.

Table 1. Sludge analysis (Werther and Ogada, 1999).

Proximate analysis	
moisture (f_{H2O} wt% raw)	76.0
char (f_{char} wt% dry)	3.6
volatiles (f_{vol} wf% dry)	45.4
ash (f_{ash} wf% dry)	51.0

After entering the furnace, sludge is decomposed into four phases under heat effect: water vapour, char, volatiles and ash, which play different roles:

- To guarantee self-combustion, the sludge produced by the wastewater treatment process sludge is dewatered mechanically to about 76% of moisture (f_{H2O}).

- Sludge char, in a solid phase that can burn, presents a very low fraction (f_{char}), unlikely carbon and biomass chars. Based on numerous laboratory analyses, J. Werther and T. Ogada (Werther and Ogada, 1999) concluded that sludge combustion behaviour is mostly governed by the gaseous phase of volatiles. So char particles can be neglected.
- Volatiles fraction (f_{vol}) is large, the volatiles combustion lead to exothermic combustion and dominate the sludge combustion process, the furnace temperature and the air input.
- Ash fraction (f_{ash}) is large.

A composition of volatiles gas, issued from off-line studies, is presented in Table 2.

Table 2. Volatiles gas composition after sludge devolatilization at temperature 760°C (Werther and Ogada, 1999).

f_{CO} wt%	43.43
f_{CO2} wt%	15.39
f_{CnHm} wt%	31.12
f_{H2} wt%	3.20
Others	6.86

The chemical species, ammonia (NH_3) and cyanide (HCN), are responsible of NOx formation, and are generally not represented in volatiles. At a relatively low combustion temperature, and with a few char but many volatiles in fuel composition, NH_3 is the dominant specie (Aho *et al.*, 1993).

2.2 Fluidized bed combustor

The fluidized sludge combustor can be divided into two beds: bubbling fluidized bed and post-combustion bed, shown in fig. 1.

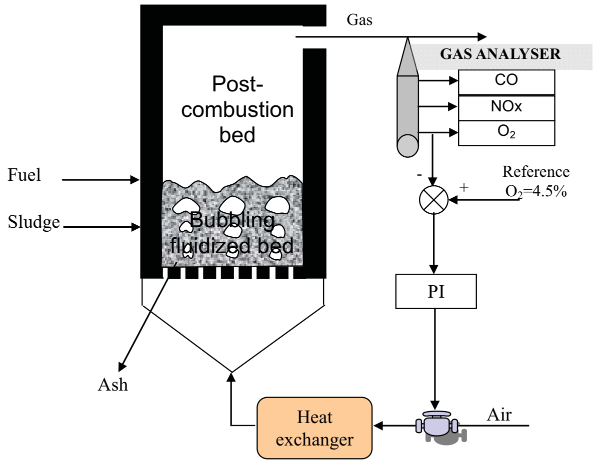

Fig. 1. Fluidized sludge combustor.

Sludge is introduced at the bottom of the furnace, i.e. the bubbling fluidized bed. Some fuel may be used as supply for starting combustion or for compensating sludge disturbances in composition or in flow. Air is preheated by a heat exchanger, and then injected with a sufficient velocity to insure the fluidization of inert sand in bubbling fluidized bed. High weight sand guarantees thermal inertia of the furnace and provides a great surface for sludge combustion and maintains a uniform temperature (~760°C). In the higher section, the post-combustion bed, volatiles gases continue post-combustion which increase the bed temperature (850°C-900°C). Temperature at the top of the furnace is limited up to 920°C, to avoid both furnace overheating and NOx formation.

The oxygen concentration is regulated up to 4.5% by air flow rate. This regulation loop provides an excess of oxygen which guaranties complete gas combustion, so as to avoid carbon monoxide (CO) formation.

On-line industrial measurements are sludge flow input in dry basis ($Q_{b,MS}^{in}$); air temperature input (T_a^{in}), air flow input (F_{am}^{in}), two bed temperatures (T^B, T^P), gas concentrations output (y_{O2} %, y_{CO} ppmv, y_{NO} mg.Nm^{-3}). As CO concentration is very low and its measurement presents lots of noise, unfortunately, this measurement can't be used for parameter estimation.

2.3 Modeling strategy and main hypothesis

The temperature and CO behaviors are described by combustion reactions. NOx formation and reduction can be considered as a separated model, using temperatures as input variables. Considering that two models has some advantages: they can be used simultaneously for simulation purpose, or separately for control purpose.

A difficulty is that sludge input flow is as constant as possible, and that sludge composition is not available on-line. So the dynamical behavior is only measured on the furnace outputs. We propose to reconstruct this composition with output measurements in the model.

As char particles can be neglected, the bubbling fluidized bed can be supposed perfectly mixed. The post-combustion bed is also approximated to a perfectly mixed reactor for model simplicity, but it is rather a plug flow reactor.

2.4 Chemical reactions

The reference (Liu and Gibbs, 2002) proposes 25 chemical reactions describing biomass combustion, including 20 reactions for NOx and N_2O formation and reduction. These reactions are selected and simplified with consideration on sludge specificities, as listed bellow:

- Due to low char content, the reactions using char as reactant and catalyst are all neglected.
- C_nH_m is supposed to be only CH_4. Its reaction is supposed to be complete in bubbling fluidized bed.
- Reaction of H_2 is supposed to be instantaneous and complete in bubbling fluidized bed.

- Catalyst as limestone (CaO), which is not used in sludge combustion, is not included.
- The lack of knowledge both on ash composition and its catalytic role (Tran et al., 2007) leads to suppose it chemically inert.
- N_2O can be decomposed rapidly in the post-combustion area where the temperature reaches 900°C. So N_2O is not considered in the model.

Five reactions are finally retained, as shown in table 3. The first reaction is NOx reduction, the second is NOx formation, and the last three are combustion reactions, which are independent from the NOx reactions. The first three reactions are supposed to be dynamically available, and the last two ones are supposed to be complete, so they do not need kinetic expression. The reactions R22, R23 and R24 are endothermic, their reaction enthalpies are noted as ΔH_{22}, ΔH_{23} and ΔH_{24}. The energy consumed or produced by the reactions R1 and R2 are negligible.

Table 3. Chemical reactions of sludge combustion model

No.	Reaction	Reaction rate r_j ($mol.m^{-3}.s^{-1}$)	Enthalpies
R1	$NO + NH_3 + {}^{1}/_{4}O_2 \rightarrow N_2 + {}^{3}/_{2} H_2O$	$r_1 = k_1[NH_3]^{0.5}[NO]^{0.5}[O_2]^{0.5}$	Negligible
R2	$NH_3 + {}^{5}/_{4}O_2 \rightarrow NO + {}^{3}/_{2} H_2O$	$r_2 = k_2[NH_3][O_2]$	Negligible
R22	$CO + ½ O_2 \rightarrow CO_2$	$r_{22} = k_{22}[CO][O_2]^{0.5}[H_2O]^{0.5}$	ΔH_{22}
R23	$CH_4 + {}^{3}/_{2} O_2 \rightarrow CO_2 + {}^{3}/_{2} H_2O$	complete	ΔH_{23}
R24	$H_2 + ½ O_2 \rightarrow H_2O$	Instantaneous	ΔH_{24}

The reaction rate r_i depends on the kinetic constant k_i and on the reactant concentrations. The kinetic constant k_i is given by the Arrhenius equation:

$$k = k_0 \exp(-\frac{Ea}{RT}) \qquad (1)$$

Where k_0 is the pre-exponential factor or simply the *prefactor*, E_a is the activation energy, R is the perfect gas constant, R=8.31 $J.mol^{-1}.K^{-1}$, and T is the temperature (in Kelvin).

To simplify validation procedure, kinetic constant k_i is supposed to be constant in one bed, so the rate constant of reaction j in bubbling fluidized bed and post-combustion bed are named as k_j^B and k_j^P.

2.5 Combustion modelling

Combustion reactions are mostly responsible for temperature and oxygen concentration in the furnace. As the combustion reactions are independent of the NOx reactions, a model of combustion can be proposed individually.

After entering the furnace, sludge particles are decomposed physically and chemically at high temperature. Firstly, drying and devolatilization take place simultaneously, splitting sludge into species described previously in table 1 and table 2. Flux of gas species can be reconstructed:

$$\begin{bmatrix} F_{H_2O}^{in} \\ F_{CO}^{in} \\ F_{CH_4}^{in} \\ F_{H_2}^{in} \end{bmatrix} = \begin{bmatrix} Q_{b,MS}^{in} \dfrac{f_{H_2O}}{1-f_{H_2O}} / M_{H_2O} \\ Q_{b,MS}^{in} f_{vol} f_{CO} / M_{CO} \\ Q_{b,MS}^{in} f_{vol} f_{CH_4} / M_{CH_4} \\ Q_{b,MS}^{in} f_{vol} f_{H_2} / M_{H_2} \end{bmatrix} \qquad (2)$$

Where F_i^{in} is the molar flow rate of component i after sludge drying and devolatilization, $mol.h^{-1}$; M_i is the molecular weight of component i, $kg.mol^{-1}$.

The volatile gas repartition is taken from table 2 without adaptation, though some relations between species fractions and temperature and fuel composition should be more realistic. With this assumption, only two sludge characteristics are needed: water fraction (f_{H2O}) and volatile fraction (f_{vol}). They are calculated by two static global balances: one is the balance of oxygen; the other is the balance of thermal energy, as shown in fig. 2.

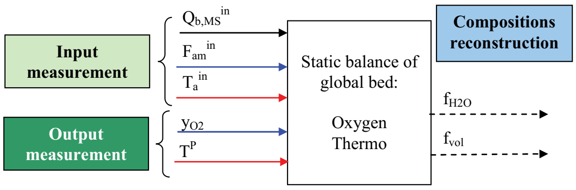

Fig. 2. Reconstruction f_{H2O} and f_{vol} from measurements (dashed line: unmeasured data, solid line: measured data).

Figure 3 presents the model structure. Three macroscopic inputs that can be easily measured (solid line): sludge flow rate in dry basis ($Q_{b,MS}^{in}$), air flow rate (F_{am}^{in}), input air temperature (T_a^{in}). State variables are gaseous species concentrations (C_{H2O}^B, C_{CO}^B, C_{O2}^B and C_{H2O}^P, C_{CO}^P, C_{O2}^P) and bed temperatures (T^B and T^P). Only four variables are measured (solid lines: C_{CO}^P, C_{O2}^P, T^B and T^P).

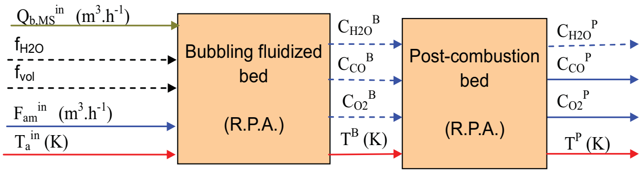

Fig. 3. Structure of combustion model (dashed line: unmeasured data, solid line: measured data).

The combustion model is written by molar and energy conservation balances (^{B} bubbling bed, ^{P} post-combustion):

$$\begin{pmatrix} \dfrac{dC_{H_2O}^B}{dt} \\ \dfrac{dC_{CO}^B}{dt} \\ \dfrac{dC_{O_2}^B}{dt} \end{pmatrix} = \begin{bmatrix} F_{H_2O}^{in} \\ F_{CO}^{in} \\ F_{O_2}^{in} \end{bmatrix} / V_B - \begin{pmatrix} C_{H_2O}^B \\ C_{CO}^B \\ C_{O_2}^B \end{pmatrix} \times \frac{F_g^B}{V^B} + \begin{pmatrix} \varphi_{H_2O}^B \\ \varphi_{CO}^B \\ \varphi_{O_2}^B \end{pmatrix} \qquad (3)$$

$$\begin{pmatrix} \varphi^B_{H_2O} \\ \varphi^B_{CO} \\ \varphi^B_{O_2} \end{pmatrix} = \begin{bmatrix} 0 \\ -1 \\ -0.5 \end{bmatrix} \times r^B_{22} + \begin{pmatrix} F^{in}_{H_2} + 2F^{in}_{CH_4} \\ F^{in}_{CH_4} \\ -0.5F^{in}_{H_2} - 1.5F^{in}_{CH_4} \end{pmatrix} / V_B \tag{4}$$

Where F_{O2}^{in} is the oxygen molar flow rate brought by input air flow, mol.h^{-1}; F_g^{in} is the global gas flow rate (calculated by a global static balance on input and output flows), m^3.h^{-1}; V_B is the bubbling bed volume, m^3; φ_i^B is the production or consumption flux of component i by chemical reactions; r_{22}^B is the reaction rate of R22 (see table 3).

$$\begin{aligned} c_{ps} m_s^B \frac{dT^B}{dt} = & \left(c_{pa} F^{in}_{am} \rho_{a\left(T^{in}_{am}\right)} T^{in}_a + c_{pb} \frac{Q^{in}_{b,MS}}{1 - f_{H_2O}} T^{in}_b \right) \\ & - \left(c_{pg} \rho_{g\left(T^B\right)} F^B_g T^B + c_{p,ash} Q^{in}_{b,MS} (1 - f_{vol}) T^B \right) \\ & - \left(F^{in}_{H_2O} L_{H_2O} \right) - \left(r^B_{22} \Delta H_{R22} V^B + F^{in}_{CH_4} \Delta H_{R23} + F^{in}_{H_2} \Delta H_{R24} \right) \end{aligned} \tag{5}$$

Where c_{ps}, c_{pa}, c_{pg} and $c_{p,ash}$ are specific heat capacities of sand, air, gas and ash, J.kg^{-3}.K^{-1}; m_s^B is the sand mass in bubbling fluidized bed, kg; ρ is the density, kg.m^{-3}; L_{H2O} is the water latent heat of vaporisation, J.mol^{-1}.

Post-combustion balances can be similarly written:

$$\begin{pmatrix} \dfrac{dC^P_{H_2O}}{dt} \\ \dfrac{dC^P_{CO}}{dt} \\ \dfrac{dC^P_{O_2}}{dt} \end{pmatrix} = \begin{pmatrix} C^B_{H_2O} F^B_g - C^P_{H_2O} F^P_g \\ C^B_{CO} F^B_g - C^P_{CO} F^P_g \\ C^B_{O_2} F^B_g - C^P_{O_2} F^P_g \end{pmatrix} / V^P + \begin{pmatrix} \varphi^P_{H_2O} \\ \varphi^P_{CO} \\ \varphi^P_{O_2} \end{pmatrix} \tag{6}$$

$$\begin{pmatrix} \varphi^P_{H_2O} \\ \varphi^P_{CO} \end{pmatrix} = \begin{bmatrix} 0 \\ -1 \end{bmatrix} \times r^P_{22} \tag{7}$$

$$\begin{aligned} c_{pg} m_g^P \frac{dT^P}{dt} = & \left(c_{pg} \rho_{g\left(T^B\right)} F^B_g T^B - c_{pg} \rho_{g\left(T^P\right)} F^P_g T^P \right) \\ & - \left(r^P_{22} \Delta H_{R22} V^P \right) \end{aligned} \tag{8}$$

Only kinetic parameters (k_{22}^B and k_{22}^P) need to be estimated, other parameters are known from literature.

2.6 NOx modelling

As the combustion model has modelled the bed temperatures and the oxygen concentrations, which can be used as inputs of the NOx model. They are provided either from the combustion model or directly by measurements.

The NOx model can be then established and simulated independently of the combustion model, as shown in fig.4.

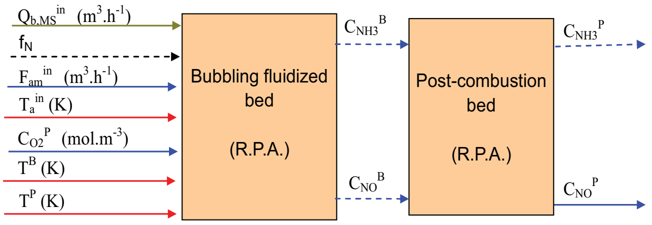

Fig. 4. Structure of NOx model.

One input cannot be measured on-line: the sludge nitrogen content (f_N), it is supposed to change slightly, and may be an additional parameter to be estimated. State variables are gaseous nitrogen species (C_{NH3}^B, C_{NO}^B, C_{NH3}^P and C_{NO}^P) among which only one is measured (C_{NO}^P).

After devolatilization, flux of NH_3 is reconstructed:

$$F^{in}_{NH_3} = Q^{in}_{b,MS} f_{vol} f_N / M_N \tag{9}$$

The balance equations are:

$$\begin{pmatrix} \dfrac{dC^B_{NH_3}}{dt} \\ \dfrac{dC^B_{NO}}{dt} \end{pmatrix} = \begin{pmatrix} F^{in}_{NH_3} \\ 0 \end{pmatrix} / V_B - \begin{pmatrix} C^B_{NH_3} \\ C^B_{NO} \end{pmatrix} \times \frac{F^B_g}{V^B} + \begin{pmatrix} \varphi^B_{NH_3} \\ \varphi^B_{NO} \end{pmatrix} \tag{10}$$

$$\begin{pmatrix} \varphi^B_{NH_3} \\ \varphi^B_{NO} \end{pmatrix} = \begin{bmatrix} -1 & -1 \\ -1 & 1 \end{bmatrix} \times \begin{pmatrix} r^B_1 \\ r^B_2 \end{pmatrix} \tag{11}$$

$$\begin{pmatrix} \dfrac{dC^P_{NH_3}}{dt} \\ \dfrac{dC^P_{NO}}{dt} \end{pmatrix} = \begin{pmatrix} C^B_{NH_3} F^B_g - C^P_{NH_3} F^P_g \\ C^B_{NO} F^B_g - C^P_{NO} F^P_g \end{pmatrix} / V^P + \begin{pmatrix} \varphi^P_{NH_3} \\ \varphi^P_{NO} \end{pmatrix} \tag{12}$$

$$\begin{pmatrix} \varphi^P_{NH_3} \\ \varphi^P_{NO} \end{pmatrix} = \begin{bmatrix} -1 & -1 \\ -1 & 1 \end{bmatrix} \times \begin{pmatrix} r^P_1 \\ r^P_2 \end{pmatrix} \tag{13}$$

Only kinetic parameters (k_1^B, k_1^P, k_2^B and k_2^P) need to be estimated, other parameters are known from literature.

3. VALIDATION

3.1 Validation strategy

Because of bad numerical results, it is not possible to simulate the model with the parameters at their literature values. The proposed validation strategy is based on some physical considerations and sensitivity analysis. As the number of parameters is numerous, only some kinetic parameters are estimated. This choice is made on the consideration that they influence directly the dynamic behaviour of the model, and that the literature values were proposed from chemical engineering laboratory analysis of coal combustion, which means that the identified values may very different.

Another important choice was to identify the parameters with two separated models or with a global one. In the first step, we choose the first solution considering that NOx content can't influence the furnace temperature. In addition, temperature is difficult to be estimated accurately with a model, though its measurement is quite reliable. Some attempts for identification with the global model have not improved the results. The main drawback of validation is that part of sludge composition (f_N, f_H) has to be fixed for each data set. Now it is adjusted by trial and error, but it would have to be further included in global parameters.

3.2 Industrial data file for parameter estimation

Two industrial data files of an industrial fluidized sludge combustor with different events are used for parameters estimation and model validation. The data used for identification corresponds to the introduction of fat matters in furnace. Model input measurements are shown in fig. 5.

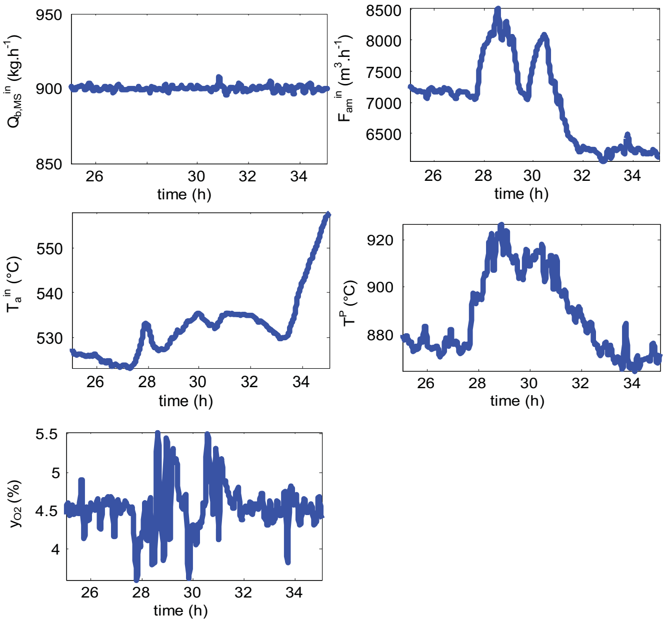

Fig. 5. Measurements of model input of data file 1.

Sludge flow ($Q_{b,MS}^{in}$) in Fig. 5 is constant, which is a necessity as sludge has to be treated continuously. The dynamic event is revealed by output measurements, which affect the input by the heat exchanger (T_a^{in} is defined by T^P) and the oxygen control loop (F_{am}^{in} is the action which regulates y_{O2}). The post-combustion temperature presents an increasement due to the dynamic event. The oxygen concentration (y_{O2}) is regulated at reference point 4.5%.

3.3 Parameter estimation methodology

For parameter estimation, minimisation of a least square criterion on the difference between the measured value and the model value has been carried out.

For combustion model, only temperature to be used is T^B, as T^P is used to reconstruct the sludge compositions f_{H2O} and f_{vol}. Consequently, the parameter k_{22}^P, can't be estimated. Some additional measurements, such as y_{CO}, may be useful for estimating this parameter. In the model, k_{22}^P is taken as a great value to guarantee a complete CO combustion, because CO in the measurement is almost null in the sake of oxygen regulation.

For NOx model, four kinetic parameters k_1^B, k_2^B, k_1^P and k_2^P need to be identified. Their literature values, calculated from steady temperature values (T^B=752°C, T^P=870°C) are presented in table 4.

Table 4. Literature values of parameters to be estimated

$k_1^B = 0.4$	$k_1^P = 7.2$
$k_2^B = 0.02$	$k_2^P = 0.87$

Because of the great number of parameters to be estimated with only one measured data y_{NO}, a sensitivity analysis is made to select the more influent parameter. Figure 6 shows that k_1^P is the most sensitive parameter with respect to y_{NO}. Finally, only the parameter k_1^P is estimated as a constant, the others are used with their reference values.

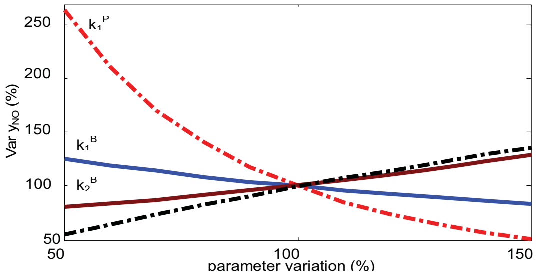

Fig. 6. Sensitivity analysis of k_1^B, k_2^B, k_1^P and k_2^P with respect to y_{NO}.

3.4 Estimated Parameters

The initial value of k_{22}^B=3.25×10^{7}exp(-15098/T^B) (14)

Which lead the equation (15) after estimation:

$$k_{22}^B=(2211\pm5)\exp(-(7743\pm2)/T^B) \quad (15)$$

The estimated value of k_1^P:

$$k_1^P=0.9981\pm0.0035 \quad (16)$$

The estimated values are all very small compared to the literature values. These differences can be attributed to the great simplifications of chemical reactions: neglected char, instantaneous and complete reactions of H_2 and CH_4 in the bubbling bed, which need to slow the global combustion reactions. For post-combustion, perfectly mixed reactor may also be revised. Some tests with other initial values have leading the same results. However, the precision interval points out that no better values can be estimated.

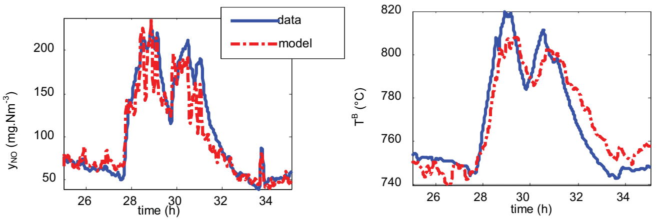

Fig. 7. Comparison of data file and model with kinetic parameter estimated k_{22}^B and k_1^P.

With the estimated values in equation (15) and (16), simulation results are shown in fig. 7. Bubbling fluidized bed temperature (T^B) in combustion model is tracking well the measurement, and NOx model fits also very well the measured data. In conclusion, we can consider that the model is realistic and these results are good enough to continue a validation step.

3.5 Validation with data file 2

The main characteristic of data file 2 (fig. 8) is an increase of the operating point: NOx concentration exceeds the norm of 400 mg.Nm^{-3}, post-combustion bed temperature (T^P) is upper the limitation value of 920°C. The sludge flow rate ($Q_{b,MS}^{in}$) remains constant at 900 kg.h^{-1} and is not represented. The air flow rate (F_{am}^{in}) and the oxygen concentration present small fluctuations around a reference point.

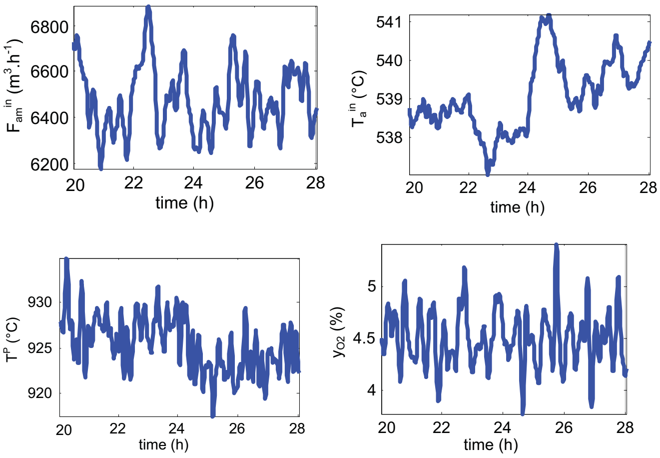

Fig. 8. Measurements of model input of data file 2

When analysing the measurements, we can notice that the bed temperatures increase greatly but fewer oxygen is consumed due to perturbation reconstruction of water fraction and volatile fraction. Trying to translate this behaviour in the model, the following adjustments are made: the hydrogen fraction (f_{H2}) after devolatilization is decreased from 3.2% to 2% (see table 2), the nitrogen fraction (f_N) is increased from 1% to 2.5%. Both corrections are used to fill up the unknown perturbations.

Figure 9 compares the simulation results with the measurements. We can see that the global tendency is good, and that means that our model is able to fit the data. The fluctuations observed for the model are due to algebraic equations for the reconstruction of f_{H2O} and f_{vol}. The main drawback is that the lack of knowledge on the input composition is a major obstacle to such modelling.

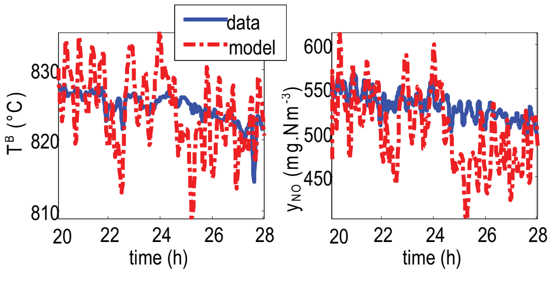

Fig. 9. Model validation.

4. CONCLUSIONS

A dynamic model of fluidized bed sludge combustor has been designed to predict NOx emissions. The main hypothesis is the lack of reactant particles in the furnace, leading to only five chemical reactions and simplifying hydrodynamics into two perfectly mixed reactors. As the sludge composition is not available, it has been reconstructed with output measurements. This point represents the main drawbacks of the model: more knowledge on devolatilization and/or more output measurements would be very helpful to have a deterministic model. However this model has been partly validated with industrial data files, and it is sufficiently representing the NOx formation behaviour, to be used in a control strategy and therefore to contribute to improve combustion quality and control NOx emissions.

REFERENCES

Adanez J., Gayán P., Grasa G., Diego L.F., Armesto L., Cabanillas A., (2001), Circulating fluidized bed combustion in the turbulent regime: modelling of carbon combustion efficiency and sulphur retention, *Fuel*, 80, 1405-1414.

Aho M.J., Hämäläinen J.P., Tummavuor J.L., (1993), Importance of solid-fuel properties to nitrogen-oxide formation through HCN and NH3 in small-particle combustion. *Combustion Flame*, 95, 22-30.

Bittanti S., Bolzern P., Campi M.C., Marco A., Poncia G., Prandoni W., (2000), A model of a bubbling fluidized bed combustor oriented to char mass estimation, *IEEE transactions on control systems technology*, 8 (2).

Gogebakan Y., Selçuk N., (2004), Assessment of a model with char attrition for a bubbling atmospheric fluidized-bed combustor, *Combust. Sci. and Tech.*, 176, 799-818.

Huilin L., Guangbo Z., Rushan B., Yongjin C., Gidaspow D., (2000), A coal combustion model for circulating fluidized bed boilers, *Fuel*, 79, 165-172.

Ikonen E. and Kortela U., (1994), Dynamic model for a bubbling fluidized bed coal combustor, *Control Eng. Practice*, 2 (6), 1001-1006.

Liu H., Gibbs B.M., (2002), Modeling of NO and N2O emissions from biomass-fired circulating fluidized bed combustors, *Fuel*, 81, 271-280.

Marias, F., Puiggali, J.R., Flamant, G., (2001), Modelling for Simulation of Fluidized-Bed Incineration Process, *AIChE Journal*, 47, 1438-1460.

Muir J.R., Brereton C., Grace J.R. and Lim C.J., (1997), Dynamic modeling for simulation and control of a circulating fluidized bed combustor, *AIChE Journal*, 43 (5).

Reimann D.O., (1999), Problems about sludge incineration, *Proceedings of the Workshop on "Problems around sludge", session 3: Technology and innovative options related to sludge management*, Stresa, Italy, 3, 173-183.

Tran K.Q., Kilpinen P., Kumar N., (2007), In-situ catalytic abatement of NOx during fluidized bed combustion – a literature study, *Applied Catalysis B: Environmental*, 2007.

Werther J., Ogada T., Sewage sludge combustion, *Progress in energy and combustion science*, 25, pp. 55-116, 1999.