EXPERIMENTAL MODELING OF NOx EMISSIONS IN MUNICIPAL SOLID WASTE INCINERATOR

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Abstract: The problem of experimental analysis and modeling of nitrogen oxide emissions in a municipal solid waste incinerator is addressed in this paper. Identification of a continuous-time model from input/output data is presented here as an alternative to physical modeling. Identification results are discussed and cost effective propositions are made to achieve reduction of nitrogen oxide emissions in municipal solid waste incinerators by improving the air feeding control system. Copyright © 2002 IFAC

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1. INTRODUCTION

Municipal Solid Waste (MSW) incineration with grate combustion furnace is a well established reliable and economic method to convert waste to nonharmful products, and to reduce waste disposal. Due to the continuously changing waste composition and heating value, MSW incineration is one of the most complex industrial processes presently in use. In order to improve the design of MSW Incinerators (MSWINc) large research programs have been performed, using physical modeling techniques and experimental investigation on full-scale and pilot-scale equipment in UK (Nassereh et al., 1994), The Netherlands (Kessel, 1995), Sweden (Dong, 1998), Switzerland (Olsommer et al., 1997), and France (Bouillou, 1996).

More and more stringent regulations are established to reduce air emissions and to improve residuocompliance with waste treatment facilities. The concentrations of certain pollutant components in flue gases (Hg) can...
only be slightly influenced by changing combustion conditions. These components have to be removed from the flue gas by a cleaning unit. Concentration of other gaseous pollutant components as CO, and nitrogen oxides NO₂ can be reduced by optimizing combustion conditions. Due to a considerable amount of chemically bound nitrogen in the waste and locally high temperature in the furnace, NO₂ concentrations in flue gas of MSWI are significantly higher than those of fossil-fuel power plants. NO₂ emission limits of 300 to 500 mg/Nm³ at 11 % O₂ dry are typical, where the NO₂ concentration corrected at 11 % O₂ is computed from the measured NO₂ and O₂ concentrations as follows:

\[ A_{NO_2,11\%} = A_{NO_2} \frac{21 - 11}{21 - A_{O_2}} \]

(1)

It has been reported that NO₂ have harmful effects on animal and plant life (Elichegaray, 2001). A recent new European directive on waste incineration (EC, 2000) limits the NO₂ emissions to 200 mg/Nm³ at 11 % O₂ dry, for MSWI whose load exceeds 6 tons of waste per hour, from December 28th 2005 on. An attempt to explain the chemical mechanisms that form NO₂ in combustion is presented in (Stoffel and Riccius, 1999). Based on this knowledge, primary techniques for improving the air distribution and combustion control, represent a highly cost effective way of reducing NO₂ formation. However to meet the daily average NO₂ emission limit of 200 mg/Nm³ at 11 % O₂ dry, secondary techniques are necessary. These abatement techniques reduce the NO₂ produced by the combustion process. They rely upon the injection of a reagent to reduce the NO₂ to nitrogen and water. However, it has been shown on full-scale equipment (Jorgensen and Madsen, 1999; Scatter et al., 1999) that combining primary and secondary techniques offers the advantage of reduced reagent consumption costs.

To obtain an accurate mathematical representation of NO₂ emissions, classical approaches use fluid dynamic modeling, which requires a good physical knowledge of the process. They are based on balance equations and lead to complex models, often inappropriate for control design. Process identification represents an alternative to this physical modeling. Different model identification approaches have already been applied to predict fossil-fuel (Dali et al., 1998; Liu and Daley, 2001) and MSW-fuel (Matsumura et al., 1998) NO₂ emissions.

This paper describes the first results of the practical application of continuous-time model identification techniques (Sinha and Rao, 1991; Garnier and Mensler, 2000) to model NO₂ emissions. The aim is here to analyze the effect of manipulated variables of the process on NO₂ emissions and to estimate a linear dynamical model of these emissions from experimental data. The paper is organized as follows. The plant is described in section 2. Section 3 is then devoted to the identification procedure and results. Pieces of discussion and interpretation are finally given in section 4.

2. PLANT DESCRIPTION

2.1 Description of the MSWI

![MSWI with grate combustion furnace](image)

Fig. 1. MSWI with grate combustion furnace

Experiments were performed on a MSWI with grate combustion furnace. The plant is organized into three classical subsystems, depicted on figure 1: a furnace, a boiler and an Air Pollution Control System (APCS).

The furnace has been designed by Martin to burn 5 tons of waste per hour. The waste is introduced on a grate by a feed ram. It is transported on this grate into a drying, a burning and a burnout zone, and agitated. For complete combustion to occur by preventing unburnt materials, air is injected into the furnace in two locations by separate systems: under the grate (primary air or underfire-air) and above the grate to mix additional oxygen with the combustion gases (secondary air or overfire air). Temperature (\(T_{Boiler}\)) and oxygen concentration (\(A_{O_2}\)) of flue gas entering the boiler are respectively controlled by adjusting waste flow (\(F_{Waste}\)) and primary air flows (\(F_{Air1}\)) entering the furnace.

The boiler is similar to those employed in fossil-fuel power plants. It operates here at a pressure of 34 bar, supplying 13 tons of steam flow (\(F_{Steam}\)) per hour at 350 °C for electric power generation.

The APCS employs whitewash injection system for acid-gas (\(HCl, SO_2\)), dry powdered activated carbon injection system for dioxin and furan and bag filter for particulate removal. Low amounts of pollutants are emitted in the flue gas. However as
there is neither primary nor secondary techniques for reducing \( NO_x \) emissions \( (A_{NO_x}) \), daily averages of 450 \( mg/Nm^3 \) at 11 \% \( O_2 \) are measured.

2.2 Waste combustion and \( NO_x \) formation

Waste combustion is a rapid exothermic reaction between waste and the oxygen source in the air. The desired combustion reactions are between carbon (C) and oxygen producing carbon dioxide \( (CO_2) \), and between hydrogen (H) and oxygen, producing water vapor \( (H_2O) \). Incomplete combustion of organic compounds in the waste produces some carbon monoxide \( (CO) \) and carbon containing particles (e.g. dioxin and furan). The sources for nitrogen-oxygen compounds \( (NO_x) \) are the air and the waste feeding the furnace. The portion of \( NO_x \) compounds produced from nitrogen with waste origin is called “fuel \( NO_x \)”, while “prompt \( NO_x \)” and “thermal \( NO_x \)” are formed with nitrogen from the air. The most important part of \( NO_x \) in MSWI with grate combustion furnace has been found to be fuel-\( NO \).

In order to promote complete combustion, oxygen from the air must be injected in the furnace in a greater quantity than the stoichiometric amount. Furthermore, secondary air is injected over the grate to ensure complete combustion of gases. The oxygen concentration should be maintained high enough to ensure complete combustion, yet low enough not to cause excessive \( NO_x \) emissions.

2.3 Overview of the combustion control system

The hierarchical combustion control system of the MSWI, described on figure 2, consists of cascade and ratio control loops. It can be split up into two main functions.

The first is to regulate a primary controlled variable, the load of the boiler \( (F_{Steam}) \) to its set-point \( (F_{Steam}^{*}) \). The master controller generates the set-point of a secondary controlled variable, the flue gas temperature in the boiler \( (T_{Boiler}^{*}) \). The slave controller switches the grate drive and feeder on and off \( (Feeder) \). The secondary air flow set-point is controlled by ratio \( F_{Steam}/F_{Air2}^{*} \).

The second main function of the control system is to regulate the quality of the combustion to prevent unburnt materials in ash and formation of Products of Incomplete Combustion (PIC) in gases which are \( CO \), dioxin and furan. A master controller regulates the oxygen concentration \( (A_{O_2}) \) to its set-point \( (A_{O_2}^{*}) \), by generating the set-point of the primary air flow \( (F_{Air1}) \).

3. CONTINUOUS-TIME SYSTEM IDENTIFICATION

3.1 The identification approach

The identification approach presented here consists in reduced order model determination of \( NO_x \) emissions from input/output measurements. The industrial process identification problem may be summarized by the following steps (Sinha and Rao, 1991; Ljung, 1999):

- determining the manipulated and controlled variables for the model,
- collecting data of the process, including the design of appropriate excitation signals,
- preprocessing data to remove trends and high-frequency perturbations,
- estimating the model orders and parameters,
- evaluating the final model on its intended application.

These steps are discussed in the following sections.

3.2 Experiment design

Three kinds of experiment were carried out while respecting constraints imposed by the industrial company to not perturb the production. The first two experiments consisted in manipulating separately the set-points of the steam flow around 12.7 \( t/h \) and of the oxygen concentration in the flue gas around 7.6 \%. No sufficiently important effects on \( NO_x \) emissions could be observed to follow up these investigations. The third kind of experiments consisted in step of \( \pm 15 \% \), from 3 to 5 hours long, applied manually on the \( F_{Air2}^{*} \).

Two sets of measurements were recorded, with a sampling period of 10 seconds. Data collection for the first set lasted about 2 days and produced 16000 data samples. We refer to this set as the estimation data set, depicted on figure 3. For the second set, data collection lasted also about 2 days and produced 19500 data samples. We refer to this set as the validation data set.
Combustion analysis of a given amount of waste in a laboratory grate furnace studied by (Jabouille, 1996) have shown the influence of air flows on average $NO_x$ concentration. In the present studied MSWI, the $F_{Air1}/F_{Air}$ ratio is maintained around 70 %, where $F_{Air}$ is the total air flow ($F_{Air1} + F_{Air2}$). The steps on $F_{Air2}$ produce variations on the $F_{Air1}/F_{Air}$ ratio, depicted on figure 3. The ratio varies between 70 % and 80 %. The influence of $F_{Air2}$ on $A_{NO_x}$ is clearly noticeable. The figure confirms the result obtained by (Jabouille, 1996) showing that an optimal ratio $F_{Air1}/F_{Air}$ of 80 % leads to smaller $NO_x$ emissions. This is particularly noticeable during the time interval 48-51 h. All the previous comments suggest that the $F_{Air1}/F_{Air}$ ratio might be increased to reduce the $NO_x$ emissions.

Furthermore, under conditions of constant air flows, the waste flow $F_{Waste}$ has an influence on concentrations of both the $O_2$ and the products of combustion (e.g. $CO_2$, $H_2O$). When waste is introduced, $O_2$ concentration decreases and products of combustion increase. In a MSWI, the boiler load control loop introduces waste by feed ram strokes and grate movements, which leads to variations of the waste flow. The effects of the waste flow variations are visible on both $A_{O_2}$ and $A_{NO_x}$, as shown on figure 4 where an image of waste flow $F_{Waste}$ has been computed from the measured feed ram position. The action of oxygen concentration control loop on $F_{Air1}$ is far too slow to remove these oscillations, that is why they can be observed on $A_{O_2}$ with a magnitude up to 2 %, but also on $A_{NO_x}$ with a magnitude up to 90 $mg/Nm^3$.

3.3 Correlation analysis

The cross-correlation functions between $A_{NO_x}$ and the variables $A_{O_2}$ and $F_{Air2}$ have been computed by means of the estimation data in order to check the influence of the combustion air flows and of the waste flow. These correlation functions are depicted on figure 5.

Firstly, the $A_{O_2}$-$A_{NO_x}$ cross-correlation function has a well defined negative peak at a positive time lag of 70 seconds. Furthermore, the magnitude of the cross-correlation function decreases to zero in a few minutes. It indicates that an increase on $A_{O_2}$ precedes a decrease on $A_{NO_x}$. It can also be concluded, from figures 4 and 5, that an increase on waste flow produces a decrease on $A_{O_2}$ and an increase on $A_{NO_x}$.

Secondly, the $F_{Air2}$-$A_{NO_x}$ cross-correlation function has a positive peak at a positive time lag of 50
seconds. The cross-correlation function decreases to zero in 5 hours, which is the duration of steps on $F_{1\rightarrow 2}$. It can be concluded, from figures 3 and 5, that a decrease on $F_{\text{Air1}}$ produces a decrease on $A_{NOx}$.

3.4 Model input/output selection

From the previous correlation analysis, but also from the process analysis presented in section 3.2, the following Multi Input Single Output (MISO) continuous-time multiple transfer function model between the output variable $A_{NOx}$ and the chosen input variables $A_{O_2}$ and $F_{\text{Air2}}$ will be considered

$$A_{NOx}(s) = \left( G_1(s) G_2(s) \right) \left( \frac{A_{O_2}(s)}{F_{\text{Air2}}(s)} \right),$$

where $s$ represents the Laplace variable.

3.5 Model order and parameter estimation

Model order and parameter estimation schemes included in the CONTSID toolbox developed at the CRAN have been used. The CONTSID Matlab toolbox mainly contains time-domain identification methods of continuous-time parametric models for linear time-invariant SISO and MIMO systems operating in open-loop from sampled data (Garnier and Mensler, 2000). It is freely available for academic researchers and can be downloaded from:

http://www.cran.uhp-nancy.fr/cran/R君/code/contsid.html

Very recent extensions for the CONTSID toolbox concern the implementation of the iterative Simplified Refined Instrumental Variable for SISO Continuous-time model identification (SRIVC) first proposed by (Young and Jakeman, 1980) and revisited recently (Young, 2002). Further developments concern the extension of the SRIVC algorithm to the case of MISO systems represented by continuous-time multiple transfer function models based on original works for discrete-time multiple transfer function model estimation (Jakeman et al., 1980). The CONTSID toolbox includes also a routine related to the SRIVC algorithms which allows the user to automatically search over a range of different orders (Young, 2002) to select appropriate orders and time-delays for the model. The very recently developed and implemented algorithms have been used here to select the model order along with to estimate the parameters of the selected model structure.

The main effects on the $NO_x$ emissions are modelled by the following estimated multiple transfer function model $G(s)$,

$$G(s) = \left( \frac{-45e^{-30s}}{1 + 21s} \frac{0.065}{1 + 116s} \right).$$

3.6 Model validation results

![Fig. 6. Validation results](image6.png)

Fig. 6. Validation results

![Fig. 7. Cross-validation results](image7.png)

Fig. 7. Cross-validation results

In order to evaluate the model quality, the model output has been simulated and compared to the measured output. Validation and cross-validation results have been computed by means of the estimation and validation data sets and are presented on figures 6 and 7 respectively.

The agreement between the model and the process output is cheering for both validation and cross-validation data sets in the case of these first experimental modeling results. However further developments might be achieved to improve the model quality, as for example to use $F_{\text{Waste}}$ instead of or in addition to $A_{O_2}$.

4. CONCLUSION AND DISCUSSION

The application results of the complete process identification methodology to the $NO_x$ emissions of an industrial MSWI have been presented in this paper. The purpose of this experimental modeling procedure was to improve the understanding of $NO_x$ emissions in order to propose cost-effective solutions to reduce them. The effects of the secondary air flow in relation to the $F_{\text{Air1}}/F_{\text{Air}}$ ratio, as well as that of the waste flow in relation to
the feed ram strokes, measured on the oxygen concentration, have been analyzed and identified by a continuous-time MISO reduced-order model.

From the experimental modeling and process analysis, many strategies may now be considered. Results firstly suggest that the $F_{Air}/F_{Air}$ ratio might be increased to reduce the average NO$_x$ emissions. Secondly, quick variations on $O_2$ and NO$_2$ concentrations are related to waste flow. The magnitude of these variations might be lowered by improving the introduction of waste in the furnace or by acting on the air flows. The dynamical effect of the waste flow will consequently be analyzed from the control variable of feed ram.

In the case of another combustion control system for MSW1 designed by Ansaldo Volund, (Jorgensen and Madsen, 1999) have proposed to use secondary air flow to control small fluctuations in the oxygen concentration, which could then be maintained to a smaller mean value (5.5 %), in order to reduce fuel-NO$_2$ formation. However, despite of these improvements, secondary techniques have remained necessary to achieve European limitations of 200 mg/Nm$^3$ at 11 % $O_2$ dry. Nevertheless, these improvements in combustion control have reduced reagent consumption and equipment costs.

5. REFERENCES


