Data-driven approaches for flue gas treatment enhancement in waste to energy plants: modelling hydrochloric acid abatement

Senem Ozgen[1], Antonio Marquez[1,2], Miguel Leon[1,2], Giovanni Barba Orsato[2], Fredy Ruiz[2]

[1]LEAP s.c.a r.l. – Laboratorio Energia e Ambiente Piacenza, Via Nino Bixio 27/C, 29121, Piacenza (PC), Italy
[2]Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, P.zza Leonardo da Vinci 32, 20133 Milano (MI), Italy
Keywords: acid gas control, reactant feed optimization, data-driven model, fabric filter residue minimization
Corresponding author: senem.ozgen@polimi.it

Waste-to-energy (WtE) plants serve to reduce the volume of non-recyclable solid waste destined for landfill while simultaneously recovering energy from the combustion process. All WtE plants require an efficient flue gas cleaning system to comply with air emission standards. The treatment of the flue gas may involve multiple stages, depending on the composition. Acid gases are major components of waste incineration flue gas. High amounts of halogens (e.g., Cl) and of sulfur present in waste are volatilized in the combustion process and give rise mainly to hydrochloric acid and sulfur dioxide, and to a lesser extent hydrofluoric acid. Dry removal of acid gases from flue gas can be achieved by alkaline neutralizing agents (e.g., calcium-based compounds or sodium bicarbonate) injection either directly into the flue gas duct or in a specific reactor. A fabric filter is installed downstream to collect the reaction products. The neutralizing reaction takes mainly place in the filter cake on the surface of the fabric filter. In these systems, the reactants are usually fed in excess with respect to the stoichiometric need to ensure that no exceedances of the emission limits is observed. Commonly, the feeding rate is regulated by an automatic control system. However, conventional control strategies are not able to cope with the large variability in the acid gas concentrations due to the variations in the composition of the fuel (i.e., municipal solid wastes) and some over dosage may happen.

To enhance the economic and environmental sustainability of WtE plants advanced control strategies may be needed to minimize the alkaline reactant feed and to reduce the fabric filter residues (i.e., residual calcium chemicals or residual sodium chemicals). These advanced controllers require the development of mathematical models describing the dynamics of the processes involved in the acid gas abatement. A data-driven approach (i.e., the relationships between system input and output variables are determined directly from the system experimental data) can in some cases be preferable rather than developing analytically a physicochemical representation of the process.

The present study implemented different system identification techniques to model the hydrochloric acid gas neutralization step in a WtE plant using a data-driven approach. Black-box models were constructed based on time series of real-world plant data (i.e., inlet and outlet hydrochloric acid concentration, sodium bicarbonate feeding). The performance of both linear and nonlinear approximation structures was evaluated. The objective was to provide a model that can prove useful for the simulation of the system behavior and to predict the outlet concentration of hydrochloric acid under different conditions of input concentrations and reactant feeding rates.

Scientific innovation and relevance:

Data-driven system models and model predictive control methodologies have been studied in recent years for different applications such as wastewater treatment systems, post-combustion CO_2 capture systems, temperature control of cement calciner, etc. However their application to waste-to-energy sector for flue gas treatment optimization is yet somewhat limited. Diversly from the previous available research specifically on WtE, the present study will explore the use of nonlinear MPC for the acid gas removal control.

Approach:

To derive the data-driven models, input-output data obtained from the plant were gathered, processed and used together with model identification tools. Models with multiple inputs and a single output (MISO) have been considered, using as inputs the inlet concentration of HCl and the bicarbonate feed rate, and as output the outlet concentration of HCl. For the neutralization process, it must be highlighted that the inlet concentration of HCl is a disturbance variable, whereas the mass flow rate of reactant is the manipulated variable.

Different model structures were employed to fit the experimental data. Specifically, the so-called Nonlinear Auto-Regressive with exogenous inputs (NARX) structure 1. In these models, the predicted output (outlet concentration HCl) is a deterministic function of the present and previous values of the inputs (inlet concentration of HCl and input mass flow rate of reactant in). Both linear and nonlinear functions have been evaluated. Linear models are preferred for their simplicity and the possibility to analyze their structural properties. Nonlinear functions allow to represent more general and complex phenomena, but their interpretability is quite limited.

Each model is parametrized by 5 parameters: the regressors length, meaning the number of past values of each signal arriving to the output function (the 2 inputs and the output) used for the prediction; and the input delays, meaning the lag between the input application and its effect on the output. Linear model structures, such as ARX and ARMAX, are put to the test, but the best performance is obtained with the use of the Non-Linear ARX (NARX) models.

Preliminary results

A data set containing real-time WtE plant data is used to train model with varying parametrizations, using linear and nonlinear structures. The assessment of the models is performed on a different validation dataset (not used for training), evaluating the fitting of the predicted model output when used for predictions at 1 and 5 minutes ahead and in simulation (without any correction based on the actual model output). Table 1 shows the structure parameters and the performance obtained on the training and validation sets for the best linear and nonlinear models found during the training process. $\mathbf{n_{u1}}$ and $\mathbf{n_{u2}}$ indicate the regressors length for the inputs and $\mathbf{n_y}$ the output regressor length. The analyses have shown that the models are able to correctly predict the trend of the output concentration for low concentrations. However, when large peaks of HCl arrive to the input, only the nonlinear model is able to correctly reproduce the output dynamics, achieving a fitting close to the 70%. From the preliminary results it can be concluded that linear models are useful for short prediction horizons only, while nonlinear structures are able to reproduce the behavior of the abatement process for longer periods of time and for a larger span of the input concentration.

Once a good model has been tuned and validated, it can be used for the design of advanced control strategies, for example to optimize the usage of the neutralizing reactants. Some of these techniques are the Model Predictive Control (MPC) or Internal Model Control (IMC). This models can also be integrated in the online operation of the plant to detect anomalies in the system.

Table 1. Results of the model comparison

	$\mathbf{n_{u1}}$	$\mathbf{n_{u2}}$	$\mathbf{n_y}$	**FIT on training (%)**			**FIT on validation (%)**		
				1 min	**5 min**	**sim**	**1 min**	**5 min**	**simulation**
Linear (ARX)	3	4	4	84.9	60.3	38.7	82.3	57.1	24.3
Nonlinear (nlARX)	3	4	4	85.1	65.6	58.4	83.4	64.9	45.8