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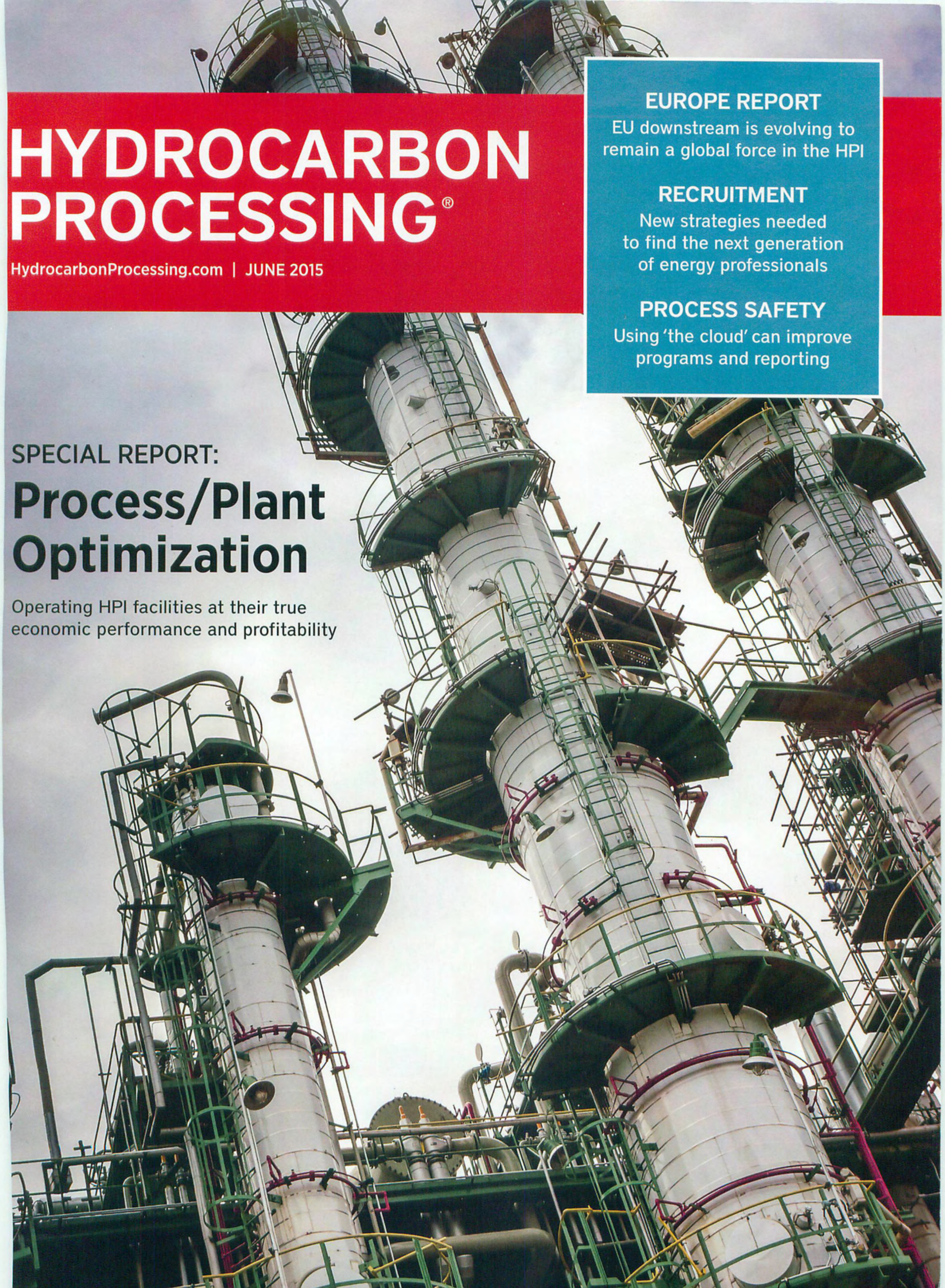

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Deploying software-based emissions monitoring systems for refining processes

In the process industries, legal requirements regulate the continuous acquisition of emissions data to monitor and control pollutants released into the atmosphere. From a plant owner's perspective, it is important that efficient and reliable tools for acquiring emissions data are available.

Environmental constraints not only can affect production, but failure to provide emissions values for extended periods may lead to an authority-imposed plant shutdown.

Typical plant continuous emissions monitoring systems (CEMSs) are essentially hardware-based. They normally include analyzers to sample and identify the compositions of released flue gas, and an IT infrastructure to manage, record and store the emissions values.[1]

Software-based predictive emissions monitoring systems (PEMSs) represent an alternative, accepted by several environmental regulations, for monitoring and recording air pollutant emissions.[2] PEMS technology can estimate emissions concentrations through advanced mathematical modeling techniques. Among the different techniques, empirical (also referred to as data-driven or inferential) modeling is recognized as the most effective in creating accurate models for estimating emissions. This approach exploits the capability to extract relevant information from historical datasets and predict the behavior of the pollutant concentrations based on the physical variables characterizing the emission-generating process itself.

In particular, artificial neural networks (ANNs), as shown in **FIG. 1,** have the flexibility to balance between model performance and robustness, providing accuracy and reliability comparable to hardware-based emissions analyzers.[3]

While US Environmental Protection Agency (EPA) legislation recognizes the possibility of adopting PEMSs as the primary source for emissions monitoring, European regulation allows the usage of PEMSs mainly as a backup of traditional CEMSs. Given the regulating framework, a major European oil refinery decided to implement a PEMS to back up the existing CEMS-based infrastructure. The goal was to increase the service factor of the hardware analysis system above 97.5% and limit the number of interventions of a third-party company to monitor the emissions during off-service periods of the hardware analyzers.

The PEMS application has been designed to provide the refinery with redundant values of different pollutant components (i.e., SO_2, CO, NO, O_2, flue gas flowrate and particulate) from two key areas of the plant: the fluid catalytic cracking unit (FCCU) and the sulfur recovery units (SRUs).

This was a very challenging application, since the units involved are much more complex than those generally deemed as the most suited for PEMS implementation (e.g., gas turbines, boilers, etc.).

SRUs. Exhaust gases were collected as they emitted from three parallel desulfurization trains, each characterized by different treatment technologies and process units downstream virtually identical Claus processes. The trains are equipped with a number of bypass valves that enable the process gas to be diverted among them as required (**FIG. 2**). The second and third trains each have different, patented tailgas treatment units (TGTUs), followed by a catalytic incineration stage. The first unit has only a thermal incinerator that allows a less efficient sulfur (S) removal. Gases sent to the SRUs come from different refinery treatments and production units. The composition and ratios of these gases are neither well known nor fixed over time: essentially, the feed comprises three streams rich with hydrogen sulfide (H_2S), carbon dioxide (CO_2) and ammonia (NH_3) in variable concentrations.

The cracking unit. A patented absorption process has been commissioned to further treat the flue gas from the FCC regenerator, reducing the sulfur dioxide (SO_2) released into the atmosphere. This new unit is equipped with its own stack (FCC-02), as illustrated in **FIG. 3.** A valve can divert the exhaust gas

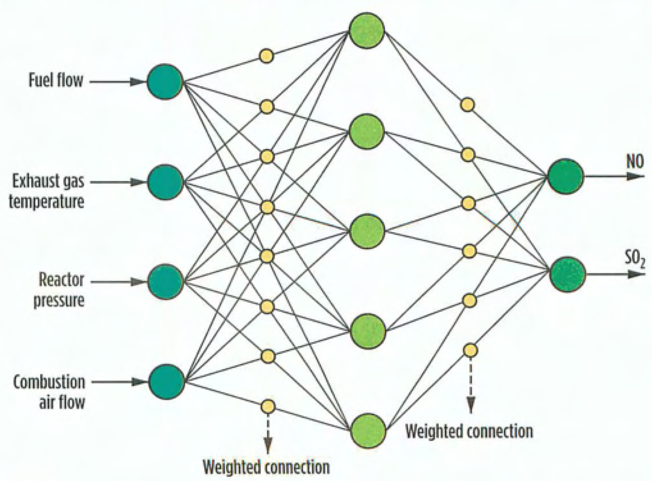

FIG. 1. ANNs are typical modeling techniques used for PEMS application.

from the cracking unit to the absorber or directly to the original stack (FCC-01).

The first complication came from the highly variable composition of the feeds, which is not under operator control and is strictly dependent on the performances of the upstream units and on the initial hydrocarbons processed by the refinery.

Process hurdles. The other critical points resulted from the large number of different operating scenarios for both units:

- The different sub-processes involved in the SRUs can be operated in a number of configurations, depending on load variations and maintenance activities that generate very different emissions levels.
- The SO_2 absorption unit is often used to comply with environmental constraints. When active, up to 50% of the FCC offgases divert to the SO_2 absorber and then to the FCC-02 stack. When the SO_2 absorption unit is inactive, all the gases enter the FCC-01 stack.

These operating challenges had a huge impact during the engineering phase and required a deep analysis of process behavior and a close cooperation with plant personnel to properly assess unit operations and available instrumentation. For the SRUs, the PEMS application was tailored to provide the best performances in the most common scenario, which also allows the highest S removal efficiency: both TGTU2 and TGTU3 are in operation, with the tailgas from the first unit diverted to TGTU2.

For the cracking unit, software analyzers were developed to provide an accurate measurement for both stacks, using the valve open-position value to identify possible shutdown of the SO_2 absorber.

Data as the cornerstone of modeling. The key requirement for effective model building is the creation of a representative dataset, a set of variables that describes process dynamics and covers all the standard operating conditions. Six months of synchronized data archived in the plant historian and in the emissions data acquisition system was extracted and analyzed.

The initial dataset was processed to finalize the subset of variables to be used for model development, performing a number of operations:

- The removal of outliers and "bad quality" data
- The identification of the proper sampling time to balance between the model overtraining and the loss of important information on process variability
- The statistical analysis through advanced mathematical techniques, such as principal component analysis, to also draw out the hidden correlations between process parameters and emission values.

Given the large number of units involved, SRU models required (on average) a set of 10–12 input parameters to ensure proper accuracy, while models for the cracking unit needed just seven or eight input variables. Several different model structures (partial least squares, linear regressions, genetic algorithms, neural networks, etc.) were generated and their performances were compared to identify the model that could more accurately reproduce emissions values. After this evaluation, the team picked feed-forward neural networks as the model architecture since it proved to be the most robust and effective for monitoring emissions.

After the offline validation, software analyzers were installed onsite in a dedicated server. An OPC connection was established to make the real-time process values from the control system available to the PEMS software engine. This module processed the parameters within the models to produce real-time emissions estimations.

The team engineers then integrated the PEMS with the existing emissions data acquisition system (DAS) to make it accessible to plant personnel (**FIG. 4**). They implemented a strategy to use PEMS values for the refinery's emissions "bubble" limit when data from the traditional instrumentation was not available.

Results. Engineers performed a comparison between the values produced by the system and the measurement by the existing hardware instrumentation. This analysis showed that predictions from software analyzers aligned very well with analytical devices: **FIG. 5** shows the predicted SRU flow values against real-time data obtained from the flowmeter mounted at

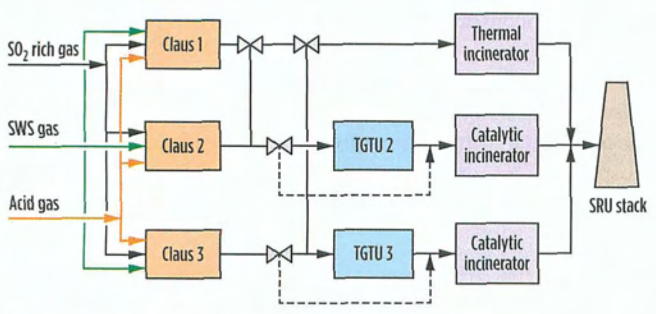

FIG. 2. SRUs layout.

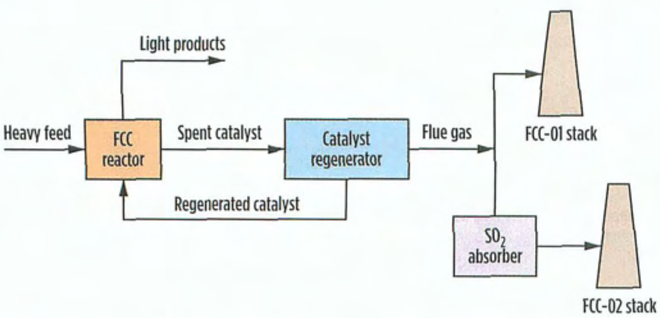

FIG. 3. FCC and absorption unit layout.

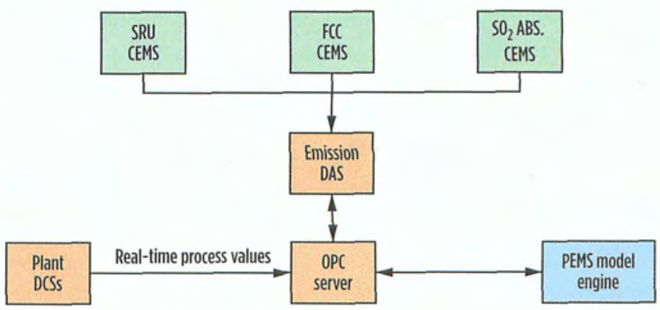

FIG. 4. PEMS architecture schematic.

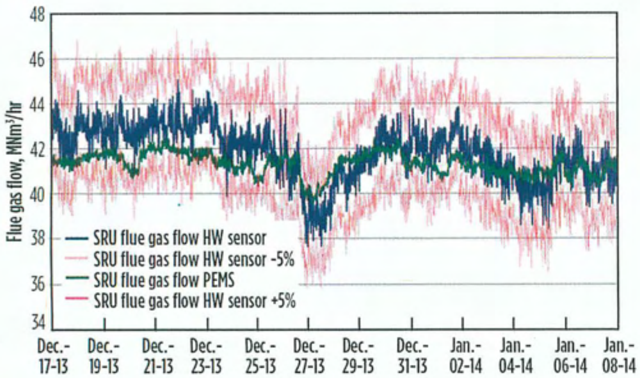

FIG. 5. PEMS vs. CEMS for flue gas flow at SRU stack.

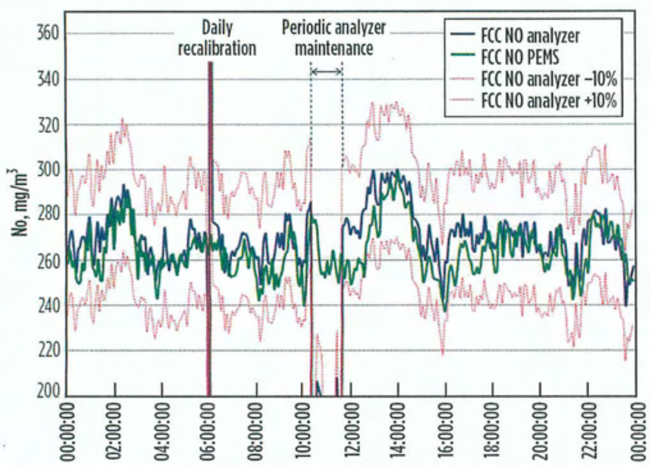

FIG. 6. A daily chart shows predicted and measured NO emissions values at the FCC stack.

stack. PEMS values are well aligned and fall within the +/-5% bandwidth from the physical measurement in the 20-day period reported. PEMS implementation was particularly important to increase the total availability of the emissions monitoring infrastructure at the site. During normal maintenance on the hardware CEMS, redundant measurements provided by the inferential models covered the blank periods.

FIG. 6 presents a daily chart showing predicted and measured nitrogen oxide (NO) emissions values at the FCC stack. Due to daily automatic recalibration and periodic maintenance activity, emissions measurements from hardware analyzers were not available in two separate intervals (one of which lasted around one hour). Thanks to the PEMS model, an alternative measurement was available and the overall service factor of the emissions monitoring infrastructure was raised well above 99%.

Benefits of predictive systems. Software analyzers proved to be an accurate and reliable backup to the traditional CEMS in very challenging refinery processes. In such applications, any discrepancy between the PEMS model output and the analytical measurement can serve as an early warning of measurement drift or malfunction of the hardware devices to trigger maintenance. The PEMSs can also represent a benchmark to validate maintenance actions.

Predictive systems provide an inherent advantage over traditional hardware-based CEMSs: the availability of a well-trained inferential model allows plant operators to perform offline simulations of emissions behavior at varying operating conditions.

PEMSs extend their contribution well beyond the CEMS backup role. Such systems have been successfully implemented as the primary monitoring technology in thousands of applications, further demonstrating their capability to offer accuracy and performance equivalent to conventional analyzers, as well as a larger data availability approaching that of DCSs (typically very close to 100%).[4]

Economically, PEMS usage provides a number of benefits when compared to traditional analyzers, beginning with an initial investment (CAPEX) that is usually considerably lower than hardware-based solutions.[5] However, it is in assessing operating costs that the PEMS advantage catches the end user's purchasing department's eyes, particularly with advantageous features, such as:

- Not requiring any specific preventive or periodic maintenance program
- Almost no power consumption
- No need for any consumables and spare parts, thus minimizing warehouse necessities.

Solutions cover a range of applications. While advanced software technologies are able to deliver excellent results in environmental projects, this does not mean that they are going to replace CEMSs. PEMSs may have an edge when applied to boilers, gas turbines or furnaces, while conventional CEMSs might prove more effective with civil incinerators or where solid fuels are burned.

Ideally, an effective solution portfolio should include both software- and hardware-based emissions monitoring strategies to cover the whole range of possible applications. HP

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