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Refinery's Process Heaters Excess Air Optimal Control

Daniel Mihăescu

LUKOIL ROMANIA- Rafinăria Petrotel LUKOIL, str. Mihai Bravu, nr. 235, Ploieşti
e-mail: dmihaescu@petrotel.lukoil.com

Abstract

This paper presents solutions to control excess air concerning refinery's process heaters. There were studied three process heaters through dynamic simulation considering feedback signals indicating CO, O_2 heater's concentrations for optimal excess air/feed fuel control. Uncontrolled excess air may produce trace amounts of incompletely burned fuel forming CO within stack gas. Continuous optimal control and monitoring for the combustion parameters enhance heater efficiency and reduced emissions. Better control strategy studied through dynamic simulation reduces O_2 from the 3 - 4% range to 1% limits the likelihood of O_2 combining with nitrogen from the excess combustion air to form NOx. Control strategy adopted within this study reduces oxygen availability decreasing NOx emissions in stack gas up to 50%.

Key words: *Dynamic simulation, combustion, optimal control, excess air*

Introduction

Romanian's refineries received recently considered as extreme importance to conduct a plant-wide energy assessment as part of the energy saving strategy. To evaluate and track implementation of the identified opportunities, part of the Romanian refiners considered highly competitive solutions in order to develop their own energy savings policies.

Studied model is a model-based, equation-oriented simulation and optimization software tool. Within environmental constraints, it optimizes the purchase, supply, and usage of fuel, steam, and power at an industrial plant furnace site. The dynamic simulation software (Aspen Dynamics) analyzes issues such as variability; alternative fuels; optimum loading of furnaces; furnace configuration; importing, self sufficiency, or export of simulation database [1].

Aspen Dynamics uses a library of furnace models specifically developed to match refinery systems, which can be tuned with real-time data to reflect current performance at a specific site. The software integrates production planning, operation optimization, contract structures, and system constraints to construct a refinery-wide flowsheet as a single, rigorous model for use by refinery management. Simulation package can be used both off-line and on-line. Off-line, the model is used for running "what-if" analyses to evaluate process changes or equipment modifications. On-line, the same model may run data validation and reconciliation routines prior to running an optimization sequence to guide operators. The optimizer determines the most economic method for meeting the refinery's steam, fuel, and power demands by calculating the optimum equipment line-up and load, subject to set constraints. Built-in equations provide information that can be used for performance monitoring. Additionally, the on-line system can provide information such as flow rates of unmetered streams. Figure 1 illustrates the flow of information through the facility and identifies simulator on-line and off-line capabilities.

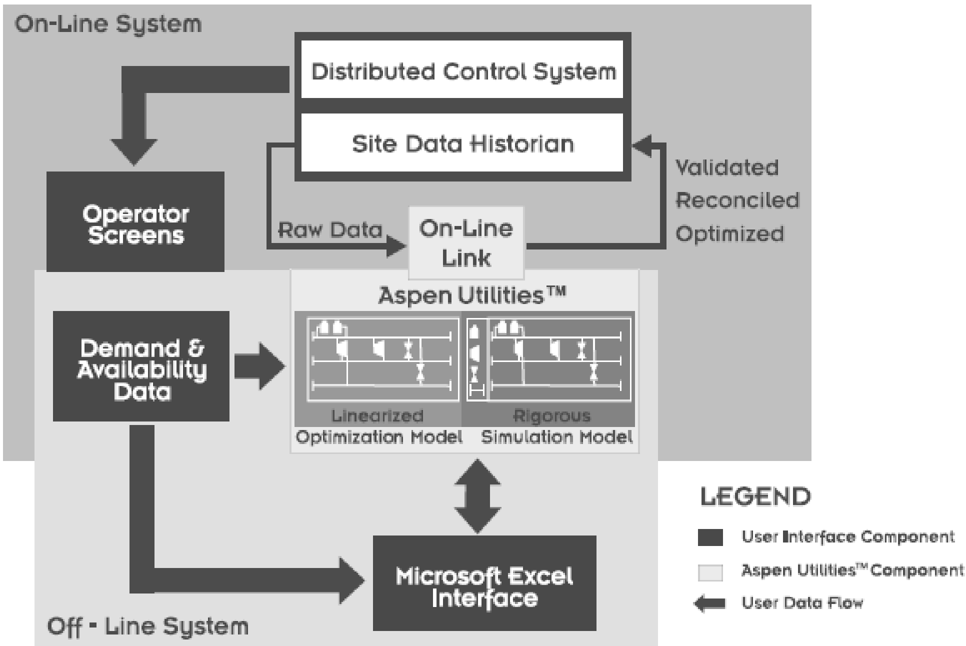

Fig. 1 Refinery energy savings control structure

The system considered to manage the refinery future energetically savings must be designed to perform the following functions:

- Facilitate optimal operations planning of utilities (fuel gas consumption especially);
- Assist in optimal operation of the utilities plant and associated equipment.
- Provide real-time information on site-wide energy performance, utility costs, and revenue.
- Provide real-time information for use in maintenance prioritization.

The excess air parameter

One kg of fuel requires a certain minimum of ambient air to be fully combusted. We call this minimum amount of air the “stochiometric air” or sometimes also “the theoretical air” to combust the fuel. The stochiometric air would completely combust the fuel to Carbon Dioxide (CO_2), water (H_2O), and Sulfur Dioxide (SO_2) if Sulfur is present. If the fuel does not get enough air for combustion it will generate smoke and a potential unhealthy mixture of stack gas products. In addition energy is wasted. The same applies if too much excess air is used for combustion. A less trivial issue in combustion technology is therefore to ensure the proper amount of air that minimizes environmental impact and fuel consumption. For convenience we define the “stochiometric air” as the air to fuel ratio, AF (kg air/kg fuel), and the excess air factor as [2]:

$$\mathrm{EA} = \frac{\text{Mass of air (kg) to combust one kg of fuel}}{\text{Stochiometric air (AF)}} \tag{1}$$

The AF is a property of a fuel that can be calculated from the ultimate chemical composition of the fuel.

Table1. Air-to-fuel ratio of various fuels

Fuel	Phase	AF	$CO_{2\,max}$ wet	$CO_{2\,max}$ dry
Very light fuel oil	liquid	14.27	13.56	-
Light fuel oil	liquid	14.06	13.72	-
Medium heavy fuel oil	liquid	13.79	14.00	-
Heavy fuel oil	liquid	13.46	14.14	-
Bunker C	liquid	12.63	16.23	-
Generic Biomass (maf)	solid	5.88	17.91	-
Coal A	solid	6.97	16.09	-
LPG (90 P : 10 B)	gas	15.55	11.65	-
Carbon	solid	11.44	21.00	-

Terminology and equations

Excess air and the excess air factor were defined in the previous paragraph. Note, that both parameters describe the same phenomena.

For instance saying a burner requires 20 % excess air to correctly combust fuel oil, is the same as saying the burner operates at an excess air factor of 1.2. A ideal combustion process would require 0 % excess air or has an excess air factor of 1.A combustion process requiring 100 % excess air uses twice as much air as necessary, or in other words has an excess air factor of two.

The technical literature and car industry reserves the Greek symbol Lambda (λ) for the excess air factor. Most modern fuel efficient cars have therefore Lambda sensors (= Oxygen sensors) to control the fuel efficiency. In boilers and furnaces they are called an "oxygen trim".

Instead of EA we will also use the symbol λ.

$$\lambda = \frac{\text{Mass of air to combust one kg of fuel}}{\text{AF}} \qquad (2)$$

The AF ratio is a fuel specific parameter that has nothing to do with the furnace design or combustion process, while λ is a parameter that tells us how efficiently a fuel was combusted. The closer λ is to one, the more efficient is the furnace or burner design and operation. Operating a boiler very close to λ =1 (or 0 % excess air) will require a "oxygen trim" that closely monitors excess air and adjusts it.

Operating very close to the minimal amount of air (= stochiometric air = theoretical air) has the inherent danger of smoke and CO generation [2,3]

Once λ is known it is fairly easy to calculate the mass of stack gas generated from the combustion process by:

$$m_{SG} = m_f\,(1 + \lambda \cdot AF) - m_{ash} \qquad (3)$$

It is worthwhile to examine the last equation. In case the furnace/boiler does not have any leaks, where stack gas escapes we can be assured that the mass entering the boiler must also leave the boiler through either the chimney or the ashbin.

In the case of oil we know $m_{ash} = 0$.

Therefore:

$$\begin{aligned} m_{SG} &= m_f\,(1 + \lambda \cdot AF) \\ &= m_f + m_f \cdot \lambda \cdot AF \\ &= \textit{fuel} + \textit{combustion air} \end{aligned} \tag{4}$$

Note that the term *combustion air* refers to dry air, excluding the humidity in air that could be anything from 1 to 20 grams of moisture per kg of air.

Derivation of excess air factor, λ

The amount of excess air cannot be measured directly, but is rather derived from a measurement of either the O2 or CO2 content of the stack gas. Whether one measures O2 or CO2 is irrelevant for the calculation of the excess air, or λ, as long as one has obtained an accurate measurement of either O2 or CO2. As previously shown in lecture 6, various sensors and methods exist to measure O2 or CO2. There is no simply and also accurate equation to calculate λ if O2 or CO2 is known. The correct equation based on a CO2 measurement is:

$$\lambda = 1 + \left(\frac{\mathrm{CO}_{2\,\max}}{\mathrm{CO}_2} - 1 \right) \cdot \frac{\mathrm{V}_{\mathrm{SG}}}{\mathrm{V}_{\mathrm{AF}}} \tag{5}$$

Where:

$CO_{2\,max}$ = the maximum CO_2 content of the dry stack gas at stochiometric combustion. Given in volume %;
V_{SG} = dry stack gas in m_n^3/kg at stochiometric condition;
V_{AF} = air-to-fuel ratio expressed as m_n^3/kg;
m_n^3 = normal cubic meter at 0 °C and 1.01325 bar.

The factor $f = \dfrac{V_{SG}}{V_{AF}}$ is between 0.93 and 0.97 for fuel oils. It is between 0.98 and 1 for solid fuels and between 0.9 and 1.9 for gases. It is best to calculate and generate appropriate charts expressing λ as a function of either O_2 or CO_2 in the stack gas by computer software.

One should appreciate the complexity involved that has resulted in quite a number of simplistic equations. Most commonly used equations are

$$\lambda = 1 + \left(\frac{CO_{2\,\max}}{CO_2} - 1 \right) \tag{6}$$

$$\lambda = \frac{21}{21 - O_2} \tag{7}$$

All equations apply only if no CO and H_2 is found in the stack gas. In case of incomplete combustion, CO is found in the stack gas. In this case λ is given as:

$$\lambda = 1 + \frac{CO_{2\,\max} - g}{g} \cdot \frac{V_{SG}}{V_{AF}} \tag{8}$$

where:

$$g = \frac{(CO_2 + CO) \cdot 100}{100 - 0.5\,CO - 1.5\,H_2} \tag{9}$$

Note that CO is commonly measured in ppm and 10,000 ppm = 1%. CO contents of 1,000 ppm = 0.1 % are considered high in the combustion of liquid and gaseous fuels.

Excess air factors found in practice

As mentioned, the excess air factor of a burner furnace or boiler is a yardstick about its efficiency as well as the skill of the operator.

Standard average figures are:

Gas burners, forced draft	1.1 - 1.3
Atmospheric gas burners	1.25 - 1.5
Oil burners	1.15 - 1.3
Coal dust burners	1.2 - 1.3
Coal firing (mechanical)	1.3 - 1.5
Coal firing (hand)	1.5 - 2.5

These are best values that can be achieved with careful monitoring and constant adjustment of the combustion air at varying loads. In reality energy auditors may see much higher numbers.

Process Heater Low Excess Air Control Dynamic Simulation Results

Petrotel LUKOIL Refinery considered operates three similar process heaters within its Catalytic Reforming Unit. Based on the study summarized within this paper I propose the refinery to upgrade both furnaces with a dedicated control system that minimizes excess combustion air. The system improves combustion efficiency and reduces oxides of nitrogen (NOx) emissions. This solution may be significantly appreciated especially due to the CE environmental regulations valid also in Romania starting with 2004.

The proposed control system for the upgrades of the above indicated Catalytic Reforming furnaces considers a low excess air control system enabling to the refiner to operate with only 1.2 % oxygen instead of the 3 to 4% that is typical in refinery process heaters. The simulation has simultaneously reduced fuel gas use in the two heaters and reduced NOx and carbon dioxide (CO_2) emissions in the heaters stack gas.

Low excess air control system proposed has been detailed within figure 2. All the three process catalytic reforming heaters studied are conventional, natural drafted that fire refinery fuel gas. The heaters must be equipped with high efficiency burners. Process operators manually adjust the burner air registers as necessary. The proposed technology may be considered as an advanced control system that automatically adjusts the heater stack damper based on carbon monoxide (CO) measurements.

An infrared spectrometer as analyzer located in the heater stack measures CO concentrations, which are considered more reliable than oxygen (O_2) measurements alone as a basis for efficiency optimization. Figure 2 shows a one of the process heaters diagram including an advanced CO control scheme [4].

Although the controls and theory for operating process heaters at optimum fuel efficiency have been around for many years, high fuel costs have only recently stimulated interest in advanced control systems. The advanced control strategy uses feedback signals indicating stack gas CO, O_2, and heater draft to automatically adjust the stack damper for optimal heater fuel efficiency. Reducing excess air produces trace amounts of incompletely burned fuel in the form of CO in the stack gas. The system may be designed to be failsafe; the continuous monitoring and fine-tuning of combustion conditions enhance heater safety. Reducing O_2 from the 3 to 4% range to 1.2 % limits the likelihood of O_2 combining with nitrogen from the excess combustion air to form NO_x. This restriction on oxygen availability reduces NO_x emissions in stack gas by up to 50% [4,5,6].

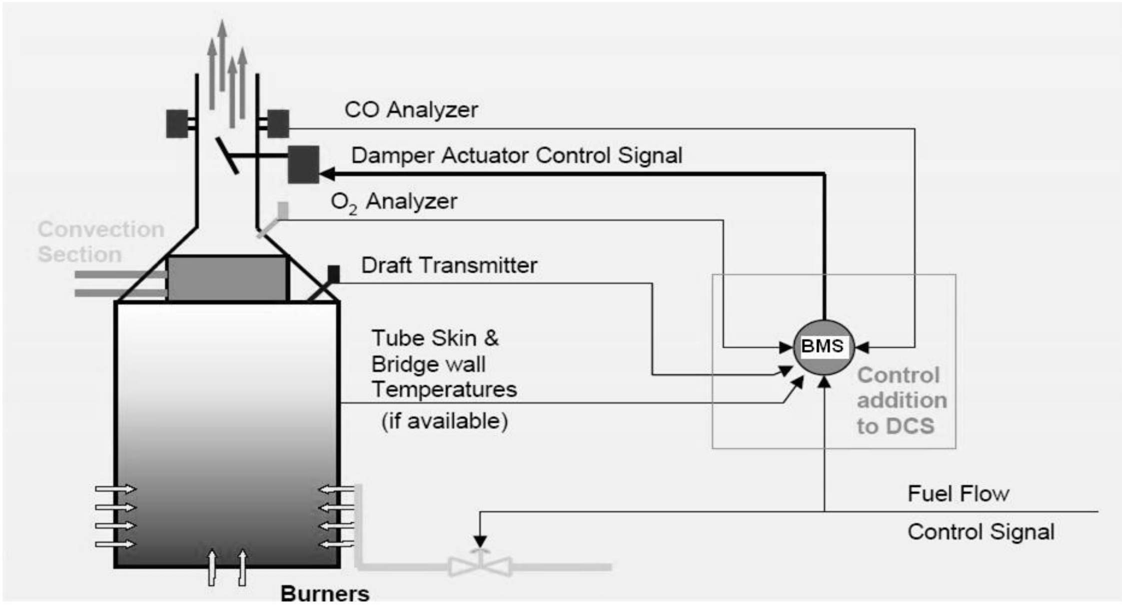

Fig. 2. Proposed excess air control diagram

Figures 3 and 4 illustrate performance data obtained by Aspen Dynamic simulation for above indicated furnaces located in Catalytic Reforming Unit. The dynamic simulation developed considered both cases: without CO Control technology implemented and also including it. The first diagram (figure 3) shows how CO increases with the decrease in oxygen, while the second diagram (figure 4) shows how closely NOx reduction is linked to oxygen levels.

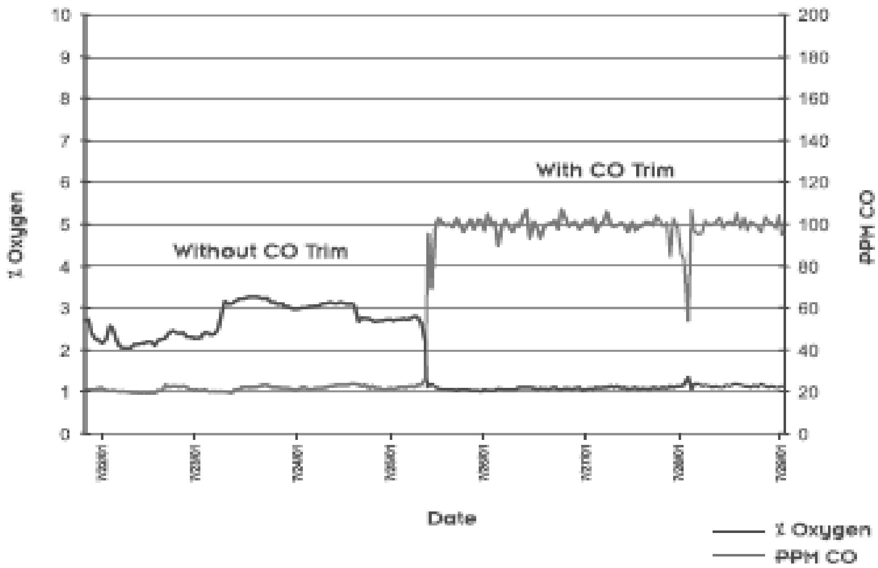

Fig. 3. Furnaces performance data

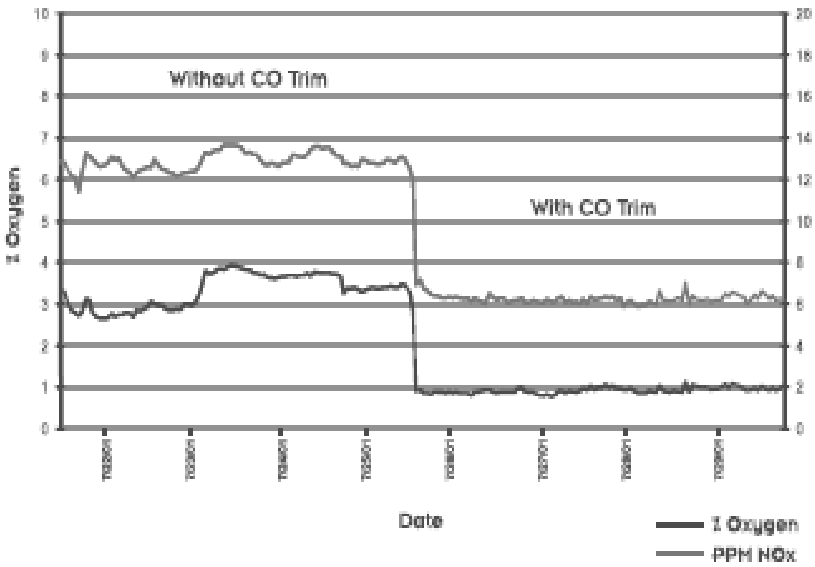

Fig. 4. Furnaces NOx performance data

Conclusions

Potential fuel gas savings at Petrotel LUKOIL Refinery were in the range of 3 to 6%, which or an estimated $340,000 per year. These savings should multiply as Petrotel upgrades additional process heaters with low excess air control proposed system.

This project will help the refinery to meet for process heaters the newly implemented europeean environmental directives concerning industrial objectives polution constraints.

Good results may be achived reducing heater stack gas NOx emissions by 10 to 25%. CO_2 emissions will also be reduced as a direct result of improved combustion efficiency.

Estimated benefits

- Fuel gas savings of 3 to 6%.
- 10 to 25% reduction in NOx emissions.
- Reductions in CO_2 emissions.
- Enhanced process heaters safety

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Reglarea optimă a excesului de aer la cuptoarele tehnologice

Rezumat

Articolul prezintă soluții tehnice privind reglarea optimală a excesului de aer necesar combustiei la cuptoarele tehnologice din rafinărie. Pentru stabilirea soluției optime de reglare autorul a analizat prin simulare în regim dinamic folosind simulatorul Aspen Dynamics cuptoare tehnologice din instalația Reformare Catalitică din rafinăria Petrotel LUKOIL. După o estimare preliminară raportată la costurile actuale aferente la 1000Nm^3 gaze de rafinărie implementarea sistemului propus de autor poate determina reducerea cheltuielilor de exploatare cu circa 300 000 USD/an pentru instalația tehnologică analizată. De asemenea soluția de reglare combustie propusă de autor permite reducerea emisiilor de NOx la coşurile cuptoarelor tehnologice cu tiraj natural cu până la 50%.