2013 European Control Conference (ECC)
July 17-19, 2013, Zürich, Switzerland.

Advanced control solutions to increase efficiency of a furnace combustion process

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Abstract — **In the present work the problem of the furnaces combustion optimization in petrochemical environment is presented. In particular, the paper is focused on the combustion efficiency that directly affects the operating costs of the plant. A preliminary study of the combustion process has been performed. A model of the system has been obtained by a black-box approach and limitations of the existing control architecture have been analyzed. A new control architecture, based on advanced PID control architecture, coupled "cross-limiting" control logics and Fuzzy logic has been developed and implemented in a Distributed Control System (DCS). The major benefits introduced by the new control system can be found in its reliability and in its robustness to compensate the measurable disturbances that affect the furnace. Moreover, the proposed control scheme has been proven to be effective in the reduction of the O_2 content in the exhaust of furnace gas as well as in the reduction of the fuel consumption. As a consequence of the O_2 reduction a reduction of the exhaust gas temperature has been achieved thus further increasing the furnace efficiency. The total efficiency increase has been estimated of about 2.2% with a significant energy saving of about 500 k€/year. Finally, the reduction of nitrogen oxide and carbon monoxide concentrations in the exhaust gases achieved by the new control strategy, allows minimizing the pollution emissions satisfying the actual national environmental requirements.**

I. INTRODUCTION

Furnaces are key equipments and major energy consumers of petrochemical industry [1]: furnaces combustion performance directly affects the quality of final products as well as the total energy consumption of the plant. In addition, a not optimal combustion may cause severe increase of the temperature and of the concentration of pollution components in the exhaust gasses. For these reasons control of furnace combustion has becomes one of the top research topics in the refinery industry. The need to enhance the efficiency level, to increase the profitability as well as the commitment to meet environmental requirements has motivated the investment in new sensor technologies and the applications of advanced control logics.

In the present paper, the performances of an existing furnace combustion control system of a refinery plant have been first analyzed. The availability of a reliable oxygen analyzer for the measurement of the percentage of O_2 in the exhaust gases at the chimney (see figure 1) and the adoption of advanced PID control strategies [2] allowed improving the typical air-fuel ratio-control scheme that couples the air flow and temperature combustion regulators of the furnace. In particular, the proposed double cross-limiting control (DCL-C) strategy is able to compensate for the large perturbations of the main combustion parameters that in the previous control scheme were observed in presence of variations of the charge feed from the upstream plants. Finally, to further increase system performances a Fuzzy controller has been developed that allows the fulfillment of transient response requirements. The controller, following a structure proposed by one of the author in a previous work [16], is based on the application of Fuzzy control techniques to guarantee the suppression or at least the limitation of the overshoot in the system response.

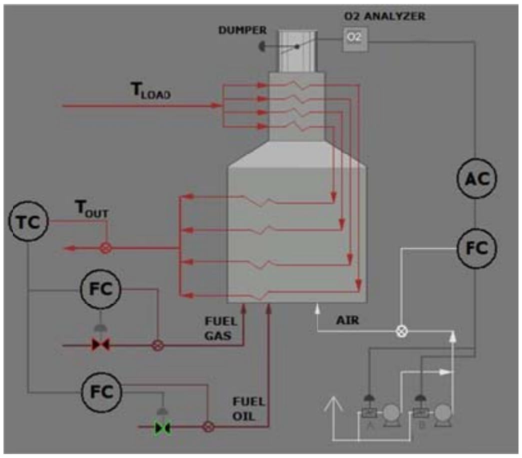

Figure 1: Furnace system

The proposed control system has been suitably implemented in the Distributed Control System (DCS) of the plant allowing a great improvement of the control performance of the original system and a significant reduction of the energy consumption and environmental pollution.

The paper is organized as follows. In Section I a brief introduction of the paper is given. Problems related to combustion in furnaces are summarized in Section II. The mathematical model adopted to describe the most important dynamics of the process used to develop and test the new controller is presented in Section III. In Section IV and V the new control strategy and the proposed Fuzzy controller are described. In Section VI the achieved results are discussed. Finally, conclusions are presented in section VII.

II. PROBLEM DEFINITION

Combustion requires a fuel and an oxidant (typically, oxygen that is present in the air); insufficient quantity of oxygen in the combustion causes fuel residues, resulting in incomplete combustion with soot. On the other hand, excessive air causes problems such as a large amount of exhaust gas and unnecessary air heating, resulting in degraded combustion efficiency. Figure 2 shows the relationship between the air-fuel ratio and the thermal losses. The green (dotted) line describes the theoretical behavior of the thermal loss with respect to the air-fuel ratio while the blue (dashed) curve represents the thermal loss due to incomplete combustion. The red (solid) curve represents the resulting behavior in terms of thermal efficiency; three different zones can be defined: for low values of air-fuel ration incomplete combustion occurs and soot and smoke with noxious particulate matter are generated (*incomplete combustion zone*) while for high ratio values thermal losses due to excessive O_2 concentrations take place (*Excessive air zone*); between the two an *Optimum combustion zone* is then defined where the maximum values of Thermal efficiency are achieved [3].

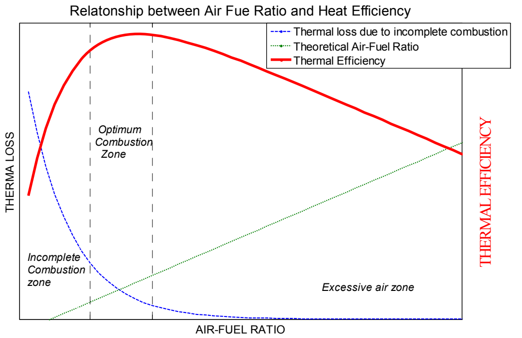

Figure 2: Relationship between Air-fuel Ratio and Heat Efficiency

For combustion furnaces such as heating furnaces and boilers in plants and factories, small-scale controllers such as single loop controllers are typically employed to optimize the air-fuel control ratio and improving the combustion efficiency. In large combustion furnaces, where distributed control systems (DCS) and advanced control techniques (multivariable predictive control, etc.) are used, typically air-fuel ratio and dumper valve (which affecting furnace internal pressure influences the furnace ventilation) are controlled so as to prevent CO, CO_2 and NOx (nitrogen oxide) from being emitted. In this way, the environmental requirements are fulfilled regardless of possible thermal losses with a consequent economic lost.

In figure 3 the Vacuum Furnace control scheme that was previously active in the plant is presented. The drawbacks of this control scheme when employed for the regulation of the furnace combustion can be summarized as:

1. %O_2 emitted with the exhaust gasses is characterized by significant oscillations;
2. Not stable values of the furnace output temperature;
3. Not stable values of the Air/fuel ratio during the transients.

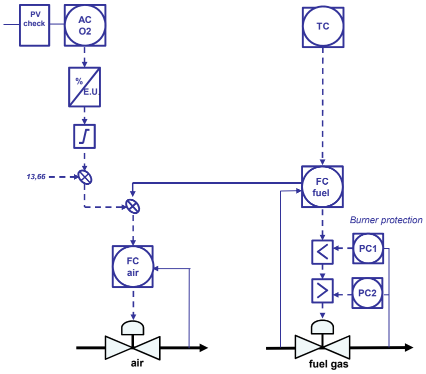

Figure 3: Existing control scheme

Before the engineering of the new control logic, the existing control system is analyzed in order to detect its critical points. The following main critical points have been individualized. Firstly, the regulation of the output temperature (TC) is realized by the existing logic through the control of the fuel gas flow (FC fuel). Hence, controlled variations of fuel gas are taken into account by the air flow controller (FC air) guaranteeing an excess of air thus preventing the incomplete combustion (see Figure 2). However no assurance of optimal combustion efficiency is given. Another critical point is the O_2 regulation in the smokes which, in the existing logic, is realized through a controller (AC O2) that checks the relationship air-fuel. This control scheme allows avoiding an excess of fuel flow but vice versa it is possible to have an excess of air flow that involves economic lost. Finally, no explicit solution accounting for the absorption of possible variations of the inlet load has been considered.

III. MODEL IDENTIFICATION

The target of the new control system strategy is to control the output temperature of the furnace and to minimize O_2 residue. Before its actual implementation in the plant, the improvements of the new control architecture have been tested offline on a simulation environment. At this purpose it has been necessary to perform a multivariable model [4] identification of the process under study. In this way it was possible to design and test a new control architecture safely performing all the necessary tuning of the proposed controllers and estimating the performance of the process in closed loop operations [5]. As it is well presented in literature [6, 17] the dynamics of many industrial processes can be well described by a simple first order transfer function with delay. In this work the generic transfer function has been chosen with the following structure:

$$g_i(s) = \frac{K_i}{1+\tau_i s} e^{-T_{d_i} s} \qquad (1)$$

where as usual K_i is the process gain, τ_i is the process time constant and T_{d_i} is the process delay. From step tests performed on the furnace under study the model of the

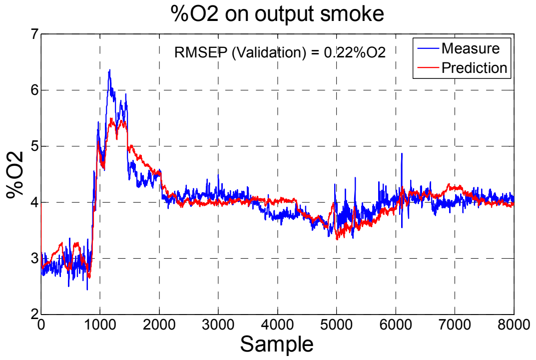

Figure 4: O_2 model validation

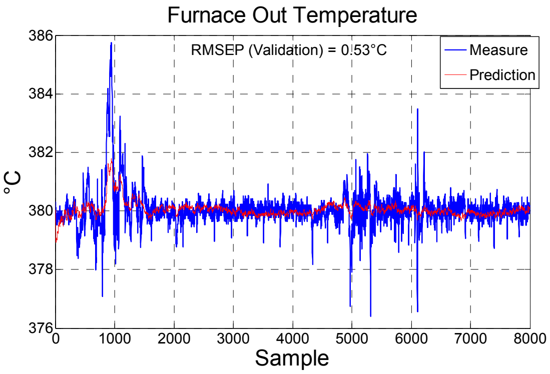

Figure 5: Out temperature model validation

process has been developed and simulated in the Matlab/Simulink environment.

In figures 4 and 5 the results of the model validation phase of the main controlled variables of the process (percentage of O_2 and furnace output temperature) are shown.

A MISO model for the prediction of the O_2 has been adopted. From the step test performed on the plant it results that the O_2 can be well predicted from the Fuel flow, the Air flows into the furnace and the Dumper valve position. The validation phase performed on a different dataset has shown a good agreement with the measurements with an RMSEP (Root Mean Square Error of Prediction) value of 0.22 percentage of oxygen as it can be seen in Figure 4.

Similarly, the output temperature resulted to be suitably predicted by the Fuel and Air flows into the furnace and the Dumper valve position. As it can be seen from the Figure 5 the model has a good agreement with the measurements: the computed RMSEP is of 0.53°C.

IV. New Control Strategy

In order to improve the performance in the regulation of the furnace output temperature and in order to minimize the percentage of O_2 in the waste gas, a new automatic control system [7] [8] [9] [10] has been designed. The new control architecture has been previously tested in an offline simulation environment, i.e. MatLab/Simulink.

The furnace uses gas as fuel and air as combustion-supporting tool. The value of air-fuel ratio directly affects the performance of the combustion control system, the quality of gasoil production, and the energy consumption. Good control of the air-fuel ratio is the key to ensure full combustion, improving combustion quality and control performance of the combustion system [11]. Many factors have been recognized causing large fluctuation of the optimal air-fuel ratio in the furnace system. For example, due to gas and air pressure fluctuations and lag of the existing control system, the actual air-fuel ratio may deviates from the system setting values.

In addition, fluctuations of the calorific value of mixed gas, which may seriously affects the furnace temperature as well as the thermal efficiency of furnace, are controlled by the temperature controller (TC, in Figure 3) causing a direct variation of the fuel flow (FC fuel) and of the air flow as a consequence of the effects of the air/fuel ratio control scheme.

In the proposed new control scheme (see Figure 6), a double cross-limiting control (DCL-C) strategy is adopted [12] with the intent to improve the combustion efficiency, to achieve accurate tracking and dynamic optimization of air/fuel ratio.

In the DCL-C system in order to prevent excessive surplus of gas or air in the secondary-loop controller, both gas and air flow measurements are considered and a mutual restraint is performed in case of sudden load variations .

Through the DCL-C, the secondary-loop controller imposes, according to output of the main loop, lower and upper bounds thus preventing, respectively, incomplete (lack of oxygen) combustion and excessive O_2 concentrations where the heat loss in the excess air is larger than the heat provided by more efficient combustion. In the new control logic when the furnace output temperature changes, simultaneous increments or decrements of the air and gas flow are performed, thus achieving best control of the furnace combustion. In figure 6 the cross limiting logic is highlighted in red color; it is possible to note that an increase or decrease of fuel or air flow, directly affects the O_2 controller and the output temperature controller, respectively.

Additionally, a feed forward logic (FF) [13] is introduced to compensate inlet feed variations and inlet temperature variations as shown in the upper and right side of figure 6. The main contribution of this feedforward component is that it prevents sudden fluctuations and perturbation of the combustion due to sudden variations of charge feed. This is particular important because in many cases these variations could otherwise lead to undesirable blocks of the process. The feedforward action has been opportunely inserted at the output of the temperature controller, instead that inserting it directly on the actuation valve. In this way, rapid variations in the actuation valve can be filtered.

Finally, a CO controller is inserted as a “guard” (see figure 6) in order to limit possible excessive decreasing of the air flow. No other organic compound has been monitored since it has been observed that the CO was the far most sensible variable to variation of O_2. Furthermore, due to the high performances of the furnace at issue the emission of NOx compounds are very limited thus not representing critical element.

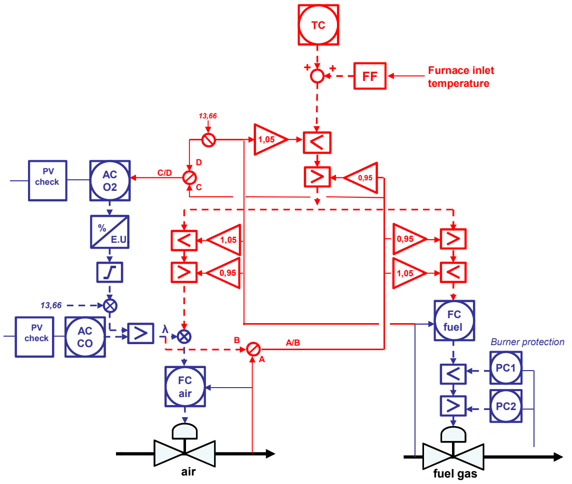

Figure 6: The proposed control scheme

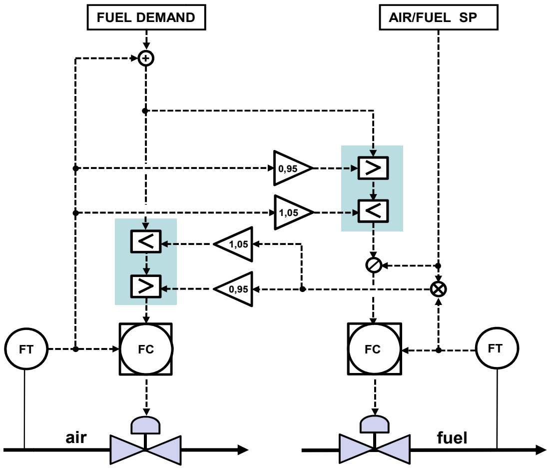

Figure 7: The “median” logic (light blue boxes) for the Air/Fuel Ratio control system

In order to assure robustness and the handling of possible process failures and faults, suitable control logics and data checking and filtering [14] have been developed such as process variables checks, blocking of the new logic in case of analyzer fail, frozen values for handling bad data and spikes detection ; in order to avoid change of the constrains operated by the operators, guard controller are implemented without SP-tracking. In case of serious CO alarms, AC and TC master controllers are set in manual operation mode.

In figure 7, the “median” blocks are highlighted: both air and fuel gas control setpoints, bound respectively to temperature and fuel gas variations, are tied to their rates with demand changes limited to plus/minus 5% for both components.

In this way the control system is able to accurately track correct air/fuel ratios over a wide range of operating parameters. In case of persistently fuel supply reductions, the mixture, until the embedded override logic can assure to keep limited the drawbacks of feed reduction.

V. FUZZY PID CONTROL

In order to obtain good performances from the point of view of the transient response behavior (limited overshoot, fast rising time, short assessing time with limited control efforts) different control approaches have been evaluated [15]. In the following of this section the results of the application of Fuzzy logic techniques for the realization of a suitable smoothing of the controller set point are discussed.

The adopted control scheme is based on a discrete fuzzy smoother (DFS) (proposed in [16] by one of the authors) that, working on-line, is able to adapt its actions to the system behavior. The idea is to drive the system with a sequence of steps, so as to keep, at opportune stages, the input signal small. In this way, since the absolute value of the overshoot depends from the value of the step change, it is possible to limit the overshoot to proper small values. An advantage of this approach is that generally a shorter rising time can be achieved.

Inputs to the DFS are: The set-point error SE = z0- z0s, where z0 is the required set point and z0s is the smoothed subset- point generated by the DFS; the error E = z0s-z, where z is the actual value of the controlled variable; the variation of the process variable is DY.

In figures 9 and 10 performances of the DFS are compared to a standard PID configuration and with a setpoint weighted PID (setpoint β = 0.7). In most of the cases the adoption of the DFS scheme allowed to eliminated the overshoot in the system response (as in figure 9) or at least, in the most critical cases, to the limit it.

This behavior is highly desirable in the considered plant since this could assure to reach the steady state response without triggering oscillations that could possibly destabilize the system.

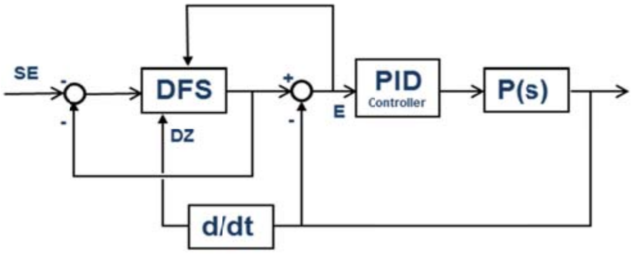

Figure 8: proposed control scheme

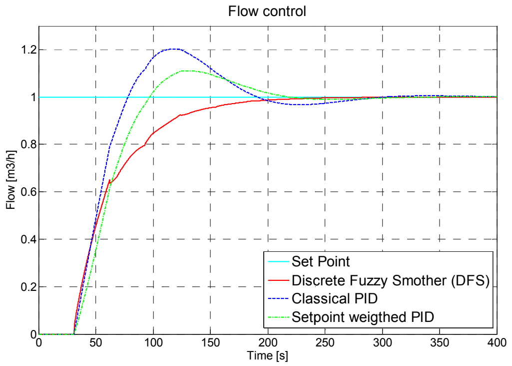

Figure 9: Flow control behaviour with different control solutions

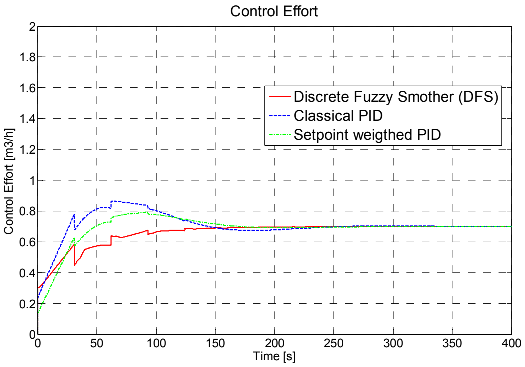

Figure 10: Control effort with different control solutions

VI. RESULTS

The improvements in the regulation of the furnace output temperature obtained by implementing the proposed control logic in the DCS are shown in the following figures. As it can be seen comparing, in figures 11and 12, the output error of the old (here named "existing") controller to that of the new ("proposed") controller, the control error has been decreased of about 41%.

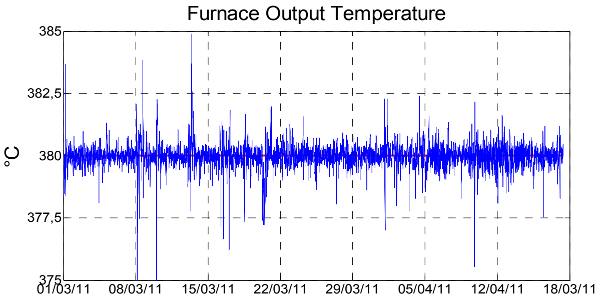

Figure 11: Output temperature with existing control scheme

Figure 12 shows the results obtained by the new control system implemented in the DCS. Comparing these results with the previously implemented control logic shown in figures 11, 13, the benefits in terms of increased noise rejection can be seen. Figures 13 and 14 show, respectively the standard deviation of the controlled output temperature for the existing and proposed control scheme: comparing the two it is clear that the proposed control scheme allows for a more effective regulation of the furnace output temperature.

In agreement, the control error in the regulation of the percentage of O_2 in the waste gas has been largely decreased obtaining a reduction up to about 75% (compare figures 15 and 16).

Similarly, the standard deviations of the controlled percentage of O2 of the two control schemes are compared in figure 17 and 18. Is it clear from the above results that the proposed control scheme allows to obtain higher economic return; in fact, when adopting the new control strategy, the O_2 working point is kept closer to the minimum target.

Finally, figure 19 shows the decrease of O_2 emission as a result of the implementation of the new control scheme.

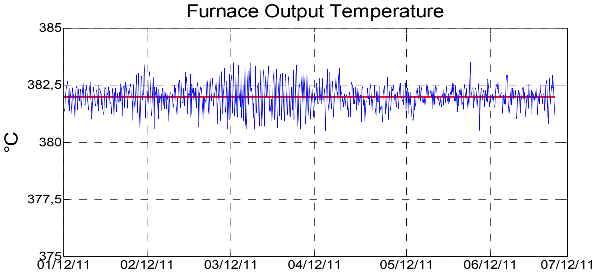

Figure 12: Output temperature with proposed control scheme

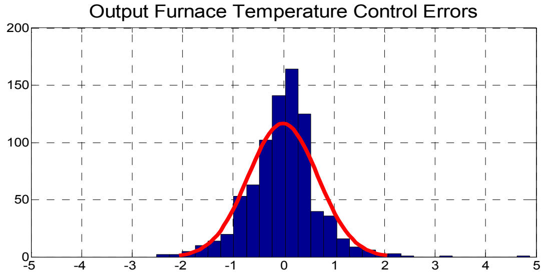

Figure 13: standard deviation of the error in output temperature with existing control scheme

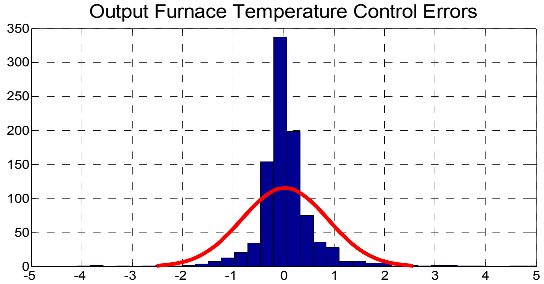

Figure 14: standard deviation of the error in output temperature with proposed control scheme

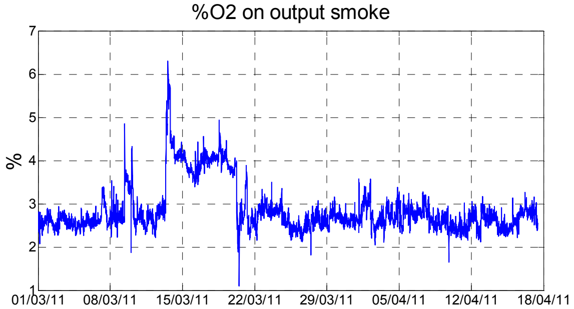

Figure 15: Percentage of oxygen on smoker with existing control scheme

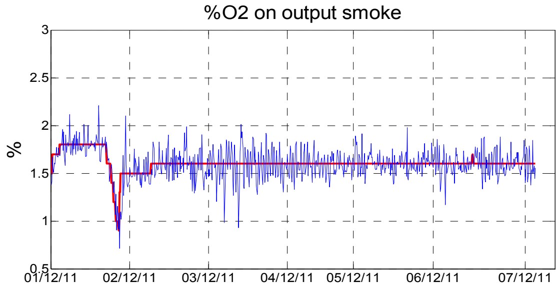

Figure 16: Percentage of oxygen on smoker with the proposed control scheme

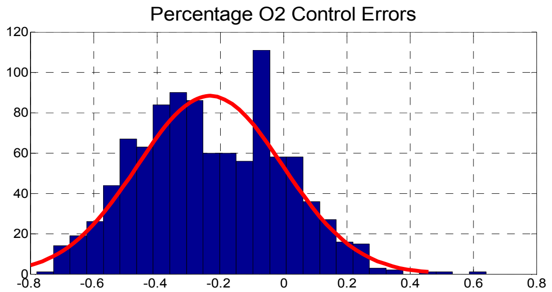

Figure 17: standard dev. of the error in O_2 with existing control scheme

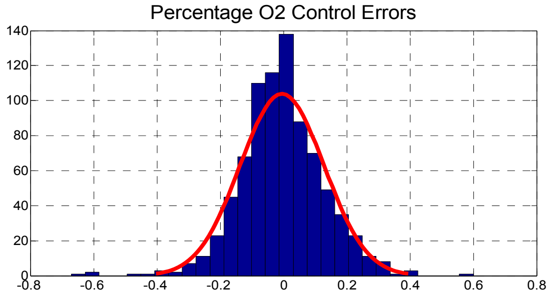

Figure 18: stand. dev. of the error in O_2 with the proposed control scheme

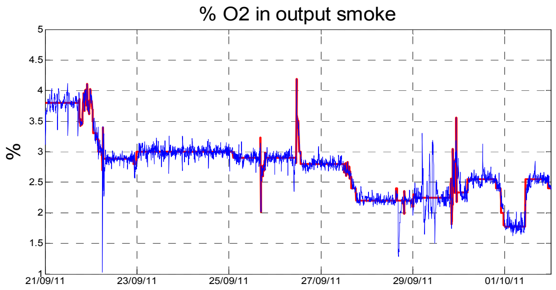

Figure 19: Decreased percentage of O_2 in output smoke obtained with the proposed control scheme

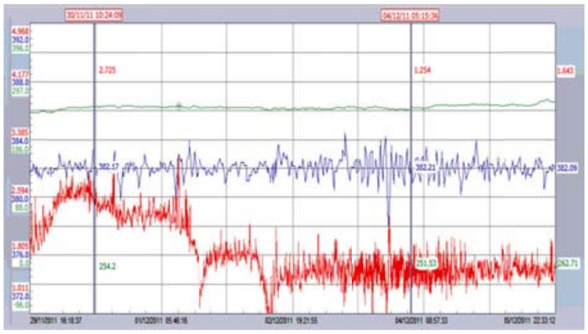

Figure 20: DCS snap-shoot highlights O_2% reduction on real system

In figure 20 a snapshot directly taken from the DCS HMI is depicted highlighting the same results of figure 19.

VII. CONCLUSIONS

An advanced PID controller architecture design that optimizes furnace combustion is presented. Process model identification has been performed and a new control solution has been proposed, analyzed and tested in simulation. As a final step the proposed control system has been suitably translated for the implementation in the Distributed Control System used in the refinery plant and it is actually operative. The implementation of the proposed system confirmed the expected high performances improvements: better stochiometric combustion constraints management; safer transit management; tighter control of output temperature and heater excess air (O_2 level optimization, CO guard controller).

The proposed Double Cross-Limiting control (DCL-C) can make the air loop and the gas loop sensitive to simultaneous variations of the gas flow, limiting effectively the actual value of the excess air rate, ensuring the combustion control system to work at optimum conditions (that is, within the optimum combustion zone), meanwhile, avoiding burning of gasoil at excessive air conditions and ensuring good quality of gasoil products. After the Double Cross-Limiting control logic and the DFS set point controller have been introduced into the furnace combustion control system, the accuracy of the gas and air flow control has been improved while the heat losses caused by excess air combustion and lacking-oxygen combustion have been considerably reduced. Thus, the system has been proven to be useful in helping to improve product quality and product yield as well as reducing energy consumption. The economic gain of oxygen optimization has been estimated to be up to 500 k€/year and even greater.

REFERENCES

[1] Speight J.G., The chemistry and technology of petroleum. CRC Press, 2006.

[2] Maples R.E., *Petroleum refining technology and economics*. 2nd Edition. Pennewell Books, 2000.

[3] Shell, *Practice Worth Replicating for Automatic Excess Oxygen Control for Natural Draft Fired Heaters*. GS.07.52472 - ECCN EAR 99 – October 2009

[4] Coughanowr D.R., *Process system analysis and control.* 2nd Edition, McGraw Hill, New York, 1991.

[5] Seborg D.E., Edgar T.F., Mellichamp D.A., *Process dynamics and control.* John Wiley & Sons, New York, 1989.

[6] Zhu Y.C., Backx T., *Identification of multivariable industrial processes for simulation, diagnosis and control.* Springer, London, 1993.

[7] Shinskey F.G., *Process Control Systems*. Mc Graw Hill, New York, 1996.

[8] Anirudda D., Ming-Zu Ho, Shankar P. B., *Structure and synthesis of PID controllers*, Springer, 2000.

[9] Luyben W.L., Luyben M.L., *Essentials of process control.* McGraw Hill, New York, 1997.

[10] Stephanopoulus G., *Chemical process control*. Prentice Hall of India, New Delhi, 1995.

[11] Shell, *Control System And Instrumented Protective Functions For Fired Equipment: Multi Burner Control*. DEP 32.24.20.37 Jan. 1998

[12] Skogestad S., Postlethwaite I., Multivariable feedback control: analysis and design, Wiley, 2005.

[13] Astrom K.J., Hagglung T., *PID controllers: theory, design, and tuning*, ISA, Research Triangle Par, 1995.

[14] Morari M., Zafiriou E., *Robust process control.* Prentice Hall, New York, 1989.

[15] Tan Kok Kiong, Wang Quing-Guo, Hang Chang Chien. *Advances in PID control*, Springer, 1999.

[16] Zanoli S.M., Conte G., *Remotely operated vehicle depth control.* Control Engineering Practice 11, 2003.

[17] Jan Marian Maciejowski, *Predictive Control with Constraint*. Practice Hall, 2002