Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Temperature control of a crude oil preheating furnace using a modified Smith predictor improved with a disturbance rejection term

R. Rivas-Perez*, V. Feliu-Batlle, F.J. Castillo-Garcia**, I. Benitez-Gonzalez***

** Department of Automatica and Computer Science, Havana Polytechnic University, Calle 114 No 11901, CUJAE, Marianao, Habana, C.P. 19390, Cuba (e-mail: rivas@electrica.cujae.edu.cu)*
*** Escuela Técnica Superior de Ingenieros Industriales, Universidad de Castilla-La Mancha, Campus Universitario s/n, Ciudad Real, C.P. 13005, Spain (e-mail: vicente.feliu@uclm.es; fernando.castillo@uclm.es)*

Abstract: This paper proposes a two degrees of freedom modified Smith predictor scheme for controlling the outlet temperature uniformity of a crude oil preheating furnace. A reliable mathematical model for describing the nominal process dynamics has been obtained from an identification procedure using real-time field data. This procedure yields a second order model with a dominant time-delay term (significantly higher than the time constant values). Moreover, disturbances have been identified as step responses of first order processes. A *PI* controller embedded in a modified Smith predictor scheme is therefore designed. A disturbance rejection term is designed for this scheme. This term is designed using a new methodology which reduces the effect of unknown disturbances on the process output. Simulations show that our proposal significantly outperforms the one degree of freedom Smith predictor and a well-known two degrees of freedom Smith predictor.

1. INTRODUCTION

Oil refining industry is one of the most complex chemical ones, with many different processes and chemical reactions and also with an impressive economic and environmental impact worldwide (Chaudhuri, 2011). In this industry, crude oil preheating furnaces are considered one of the most energy consumption plants (Masoumi and Izakmehri, 2011), in which control accuracy and temperature uniformity have a direct impact on product quality and energy consumption (Wang and Zheng, 2007). However, a significant amount of energy is currently lost in most crude oil preheating furnaces as a result of inaccurate control (Wang and Zheng, 2005).

Preheating furnaces are used to heat crude oil up to a temperature around 390-400ºC before entering to a fractionating column operating at atmospheric pressure, where the gas fraction and several liquid fractions with different boiling points are separated off (Chaudhuri, 2011). The schematic diagram of a single flow crude oil preheating furnace is shown in Fig. 1. This process is characterized by nonlinear dynamics, distributed parameters over distance, and a dominant time-delay (Wang and Zheng, 2005).

These furnaces are often operated in presence of diverse disturbances which include the crude oil outlet flowrate variations, the crude oil inlet flowrate temperature variations, variations of the fuel flowrate in the burners, changes of the fuel pressure in the burners, change in the composition, quality and calorific value of the fuel, fouling of burners, nonuniform temperature distribution in the furnace radiation chamber, the temperature of the fuel and the air, the air/fuel ratio, the heat loss to ambient, etc. (Wang and Zheng, 2007). *PI* and *PID* controllers are commonly used for temperature control of the crude oil preheating furnace in real petrochemical industrial applications (Zeybek, 2006; Chaudhuri, 2011).

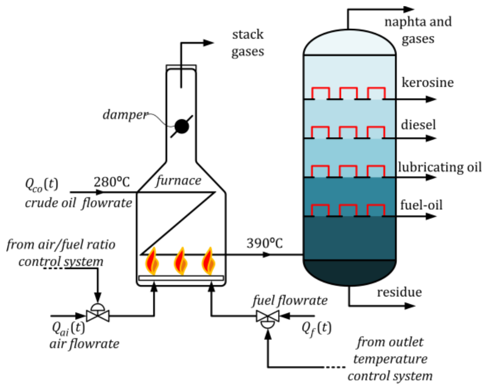

Fig. 1. Simplified scheme of a crude oil preheating furnace.

Drawbacks of the actual control strategies are that the real dominant time-delay of the reference process and the effective rejection of disturbances are not considered, which impairs the accuracy of the required temperature uniformity of the furnace use (Wang and Zheng, 2005).

On the other hand, the Smith predictor control scheme (hereinafter *SP*) is perhaps the best known and most widely used algorithm to deal with plants with large time-delay (Smith, 1959). However, although the *SP* offers potential improvement in the closed loop performance of processes with dominant time-delays, its application to industry has been limited due to some problems such as its sensitivity to modelling errors (Normey and Camacho, 2007) and its poor capability for attenuating disturbances (e.g. Palmor, 1996).

Usually, disturbances rejection of time-delay compensation techniques is effective only for processes with dominant time-delays and it deteriorates when the time-delay term is relatively small. Rivas-Perez et al. (1987) presented a 2 *DOF* modified *SP* that allows decoupling the set point tracking problem and the disturbance rejection one. This paper proposes a control system which is an improvement of the Rivas-Perez's modified *SP*. It is tuned in order to maximize the outlet temperature uniformity of a single flow crude oil preheating furnace, and improves the disturbance rejection.

The paper is organized as follows. Section 2 describes the crude oil preheating furnace under study and the experimenttal identification of a linear model. Section 3 presents the proposed modified *SP* scheme and compares it to another 2 *DOF* time-delay compensation techniques. Section 4 details the design of the controller and shows its performance. Finally, Section 5 provides some conclusions.

2. SYSTEM DESCRIPTION AND DYNAMIC MODEL

2.1. Crude oil preheating furnace description

The study presented in this paper is based on the crude oil preheating furnace of Havana petroleum refinery. The main parts of the furnace are the convection section, radiation chamber, burners, tubes, and stack. The crude oil flowrate, $Q_{co}(t)$, to be heated enters the furnace, flows inside the tubes of the overhead convection section and then descends to the radiation chamber (see Fig. 1). The heat input comes from burning fuel-oil or diesel in the radiation chamber with a flowrate $Q_f(t)$. The fuel flows into the burner and is burnt with air flowrate, $Q_{ai}(t)$, provided by an air blower. The furnace operates at a temperature between 700ºC and 900º C and the stack gases leave at approximately 750ºC. Thus the crude oil is heated from the supply temperature 280ºC to a reference outlet temperature 390ºC and then enters the atmospheric fractionating column.

2.2. Furnace dynamic model

Several mathematical models of the crude oil preheating furnaces have been proposed for control (e.g. Fuchs et al., 1993; Stehlik, et al., 1996; Masoumi and Izakmehri, 2011). However, these models are usually difficult to apply to the controller design. An alternative is to obtain linear approximation models of real preheating processes by using system identification methods, e.g. Samyudia and Sibarani (2006).

We used an identification technique to determine an approximate linear model of our process, where the fuel flowrate to the burners $u(t)$ is the input (manipulated variable) and the crude oil outlet temperature of the furnace $y(t)$ is the output (the controlled variable, hereinafter denoted as the furnace temperature). The main disturbances are the changes in the composition, quality and calorific value of the fuel, incomplete combustion of the burners, fouling of burners, etc. Their effects have been modelled as unmeasured step disturbances $d(t)$ which pass through the transfer function $W(s)$ and are added to the input $u(t)$.

Experiments based on steps responses carried out in our crude oil preheating furnace in nominal regime (from 280ºC to the nominal temperature 390ºC). In this test, the fuel flowrate valve received an increment $\Delta u(t)$ in its opening magnitude of 30%, and the furnace temperature and fuel flowrate valve opening magnitude were uniformly sampled with a period of T_s = 1 s, registered and stored in a computer. The registered data is drawn in Fig. 2. Response $\Delta y(t)$ shows that the dynamics of the nominal process can be described by a second order transfer function with a time-delay given by:

$$G_0(s) = \frac{\Delta Y(s)}{\Delta U(s)} = \frac{K_0}{(1+T_{10}s)(1+T_{20}s)} e^{-\tau_0 s}, \qquad (1)$$

where K_0 = 3.66 ºC/% is the static gain, T_{10} =51.2 s and T_{20} =12.1 s are time constants, and τ_0 = 110 s is the time delay. Fig. 2 also shows that the steady state of the furnace temperature is reached in an approximate time of $t_s^{op} = 277$ s.

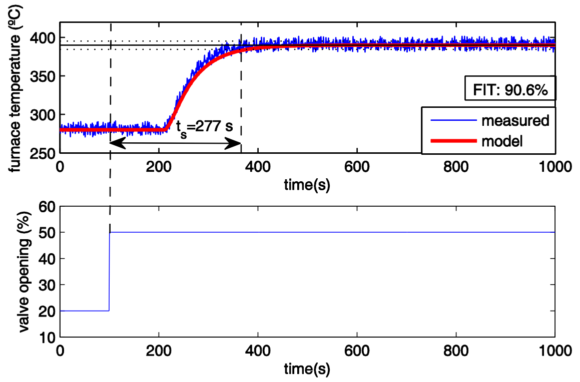

Fig. 2. Experimental step response of the nominal process, and validation of the obtained model.

Validation results of linear model (1) with the estimated nominal parameters are shown in Fig. 2. This figure shows a good agreement between the data of the step test and the predictions provided by our model. Moreover, a cross-validation test was applied to our model. The *FIT* index (considered one of the best in order to validate models and the only one that finds actual general application (Ljung, 1999)) was calculated and included in Fig. 2. Models that yield values of this index higher than 80% are regarded as very accurate in industrial processes control (Ljung, 1999). Our model yields a 90.6% FIT value.

The unmeasured disturbances were modelled as step inputs that passed through a first order filter $W(s)$, with a fitted time constant T_3=10 s. Figure 3 shows data of the effect of a disturbance (unknown) on the furnace temperature, the response provided by our model and the input disturbance used to fit such time response.

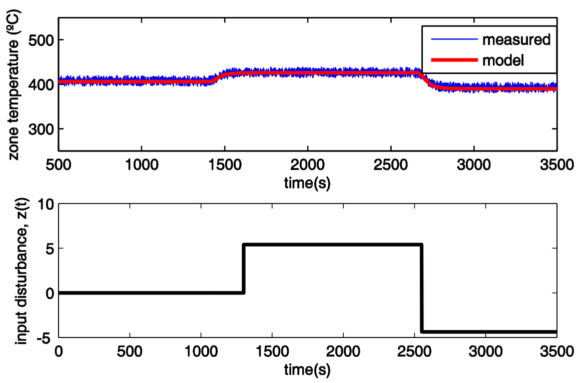

Fig. 3. Effects of non-measurable disturbances on the furnace temperature.

3. CONTROL SCHEMES

Table I summarizes the five control schemes compared.

Table I. Compared control schemes.

	Scheme	*Reference*	*Figure*
(a)	Conventional scheme	-	Fig. 4a
(b)	Smith predictor	Smith, 1957	Fig. 4b
(c)	Astrom scheme	Astrom et al., 1994	Fig. 4c
(d)	Normey-Rico scheme	Normey-Rico & Camacho, 2009	Fig. 4d
(e)	Rivas-Perez scheme	Rivas et al., 1987	Fig. 4e

For the sake of simplicity, Δ has been removed from the notation. Moreover, we made $G(s) = G'(s)e^{-\tau s}$ being G' the rational part of G.

The system response y can be written as:

$$Y(s) = M_r(s)e^{-\tau_0 \cdot s}R(s) + M_z(s)G_0'(s)e^{-\tau_0 \cdot s}W(s)Z(s) \quad (2)$$

where $Y(s)$ is the outlet temperature, $R(s)$ is the reference input and $Z(s)$ is the disturbance. Particular forms of $M_r(s)$ for schemes a) to e) are:

$$M_r^{a)}(s) = \frac{C(s)G_0'(s)}{1 + C(s)G_0'(s)e^{-\tau_0 \cdot s}}$$

$$M_r^{b)}(s) = \frac{C(s)G_0'(s)}{1 + C(s)G_0'(s)} = M_r^{c)}(s) = M_r^{d)}(s) = M_r^{e)}(s) \quad (3)$$

and particular forms of $M_z(s)$ are:

$$M_z^{a)}(s) = \frac{1}{1 + C(s)G_0'(s) \cdot e^{-\tau_0 \cdot s}}$$

$$M_z^{b)}(s) = 1 - \frac{C(s)G_0'(s)e^{-\tau_0 \cdot s}}{1 + C(s)G_0'(s)}$$

$$M_z^{c)}(s) = \frac{1}{1 + H(s)G_0'(s) \cdot e^{-\tau_0 \cdot s}} \quad (4)$$

$$M_z^{d)}(s) = 1 - \frac{G_0'(s)e^{-\tau_0 \cdot s}\left(C(s)H(s)\right)}{1 + C(s)G_0'(s)}$$

$$M_z^{e)}(s) = 1 - \frac{G_0'(s)e^{-\tau_0 \cdot s}\left(C(s) + H(s)\right)}{1 + C(s)G_0'(s)}$$

4. CONTROLLER DESIGN

4.1. Design specifications

Desired overshoot (M_p) and settling time (t_s) of the closed-loop system can be approximately achieved by designing two frequency specifications (e.g. Ogata, 1993): phase margin (ϕ_m), and gain crossover frequency (ω_c). If a second order system were used as reference, the following approximate relations would hold:

a) Phase margin versus damping ratio with an error lower than 1º : $\phi_m \approx -55.78\zeta^2 + 133.58\zeta - 0.9$, where ζ is the damping coefficient which is related to M_p by the well-known formula $\zeta = 1/\sqrt{1 + (\pi/\log(M_p))^2}$. These systems must be operated with a small overshoot. Then a design value M_p=2% is chosen for the nominal process, and the two previous expresions yield values $\zeta = 0.8$ and $\phi_m \approx 70°$.

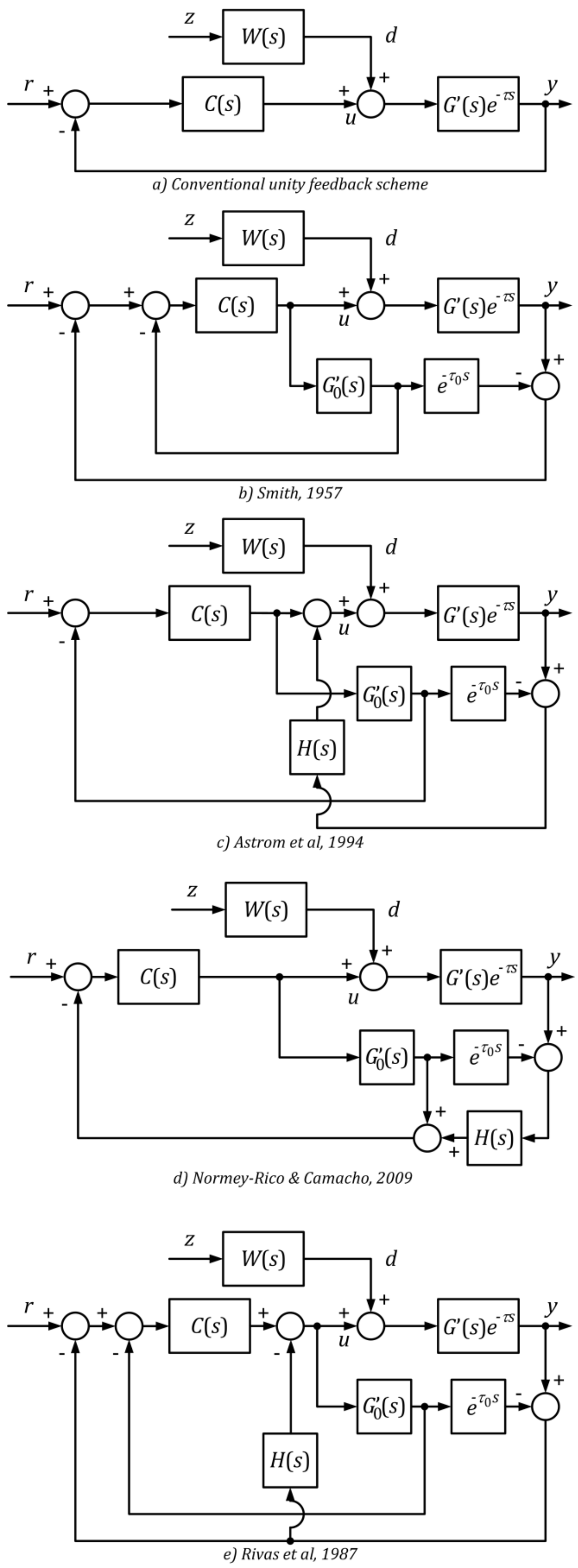

Fig. 4. Compared control schemes.

b) The closed loop settling time versus the gain crossover frequency: $t_s \approx \pi / \omega_c$. The open loop settling time of the nominal process (1) is 277 s. A closed loop settling time of 205 s is chosen, which reduces the settling time of the rational part of the process to approximately its half, e.g: 205-τ_0 = 95 s ≈ (277-τ_0)/2. Using the previous formula, a value $\omega_c = \pi / t_s = 0.0153$ rad / s is obtained.

Fulfilments of these frequency specifications will not guarantee the exact verification of time specifications because closed loop transfer functions $M_r(s)$ are not second order ones (see (3)). However, they allow designing closed loop systems in a relatively simple manner and, besides, provide information about the robustness of the control system.

If $z(t)$ were a disturbance step of amplitude A, and it were applied to the open loop system, then the steady state of the output would be K_0A. We define the settling time of the closed loop system to a step disturbance, t_{sz}, as the time needed by the response $y(t)$ to enter a band of ±5% of K_0A.

4.2. Feedback controller C(s)

PI controllers are often used in these processes, owing to its simplicity, relative robustness, and its ability to remove steady state errors from step commands and step disturbances. Then, this controller is chosen as $C(s)$ in our control schemes:

$$C(s) = K_p + \frac{K_i}{s}. \tag{5}$$

Given specifications (ϕ_m, ω_c), the tuning laws are:

$$K_p = -\Re(\chi); \quad K_i = \omega_c \Im(\chi), \tag{6}$$

where $\chi = e^{j\phi_m} / G_0(j\omega_c)$, and $\Re()$ and $\Im()$ respectively represent real and imaginary components of a complex number.

4.3. Conventional scheme

Application of tuning laws (6) yields K_p = 0.2886 and K_i=-0.0031. As $K_i < 0$, the closed loop system is unstable and the desired settling time cannot be achieved with the required damping. In fact, the minimum settling time that can be achieved by a *PI* controller with a phase margin of 70º is approximately 600 s (using a value of gain crossover frequency ω_c = 0.004 rad/s), which implies a very slow time response.

4.4. Smith predictor

In this scheme, only the closed loop dynamics of the rational part $G_0'(s)$ of the process is designed. As the settling time of this part was set to 95 s, it is obtained that $\omega_c = \pi / 95 = 0.0331$ rad/s. Then, the *PI* controller parameters are tuned using (6) with $\chi = e^{j\phi_m} / G_0'(j\omega_c)$ yielding

$$C(s) = 0.5073 + \frac{0.0092}{s} \tag{7}$$

4.5. Astrom scheme

Expression (3) shows that $M_r^{c)}(s)$=$M_r^{b)}(s)$ and then both schemes use the same controller (7). Transfer function $H(s)$ is designed taking into account that: 1) in order to get a zero steady state error to step disturbances, it is necessary to include an integral term, 2) in order to make the response as fast as possible, $H(s)$ includes a term that cancels $G_0'(s)$. A structure is therefore chosen which is a series connection of the inverse of $G_0'(s)$ and a *PI* term:

$$H(s) = \frac{\hat{K}_p s + \hat{K}_i}{s} \frac{(1+T_{10}s)(1+T_{20}s)}{K_0(1+\mu \cdot s)^2}, \tag{8}$$

where a factor $(1+\mu \cdot s)^2$ with a very small value μ has been included in order to yield a proper $H(s)$.

The characteristic equation of $M_z^{c)}(s)$ has the drawback of including a term $e^{-\tau_0 s}$. This severely limits the speed with which the disturbance can be rejected. An optimization method was applied in which frequency specifications (ϕ_m, ω_c) were varied and t_{sz} was minimized. The resulting optimum specifications are $\phi_m = 70°$, $\omega_c = 0.0331$ rad/s, which yield the following controller:

$$H(s) = \frac{0.32s + 0.0071}{s} \frac{(1+51.2s)(1+12.1s)}{3.66(0.5s+1)^2}. \tag{9}$$

Note that the design method of $H(s)$ is different from the one proposed in Astrom et al. (1994), but simpler.

4.6. Normey-Rico scheme

Firstly, we have to mention that we have removed a reference prefilter, $F(s)$, from this scheme in order to make it directly comparable to the other schemes. As it is detailed in (Normey-Rico and Camacho, 2009), this filter only affects to $M_r^{d)}(s)$. Since $M_r^{d)}(s)$ is properly stated by controller $C(s)$ and the $F(s)$ prefilter does not affect $M_z^{d)}(s)$, this assumption allows us to include this scheme in this comparison analysis.

Expression (3) shows that $M_r^{d)}(s)$=$M_r^{b)}(s)$ and then Smith predictor, Astrom and Normey-Rico schemes use the same *PI* controller (7). Following the tuning procedure described in (Normey-Rico and Camacho, 2009) and taking into account that $G_0'(s)$ has no unstable poles or zeros, $H(s)$ yields:

$$H(s) = \frac{1333.02s^3 + 136.2s^2 + 6.1517s + 0.07253}{s^3 + 4.0181s^2 + 4.0725s + 0.07253}. \tag{10}$$

4.6. Rivas-Perez scheme

This scheme yields the same performance between $r(t)$ and $y(t)$ as schemes b), c) and d), i.e. $M_r^{e)}(s)$=$M_r^{d)}(s)$=$M_r^{c)}(s)$ =$M_r^{b)}(s)$ and therefore *PI* controller (7) is used providing the same time response for nominal process.

On the other hand, for disturbance rejection, $H(s)$ can be designed in a very simple way making $H(s) = 1/G_0'(s)$ and the equivalent closed-loop transfer function yields:

$$M_r^{e)}(s) = 1 - e^{-\tau_0 s}, \tag{11}$$

and then, the effect of the disturbance is:

$$Y(s) = (1 - e^{-\tau_0 s})G_0'(s)e^{-\tau_0 s}W(s)Z(s), \quad (12)$$

which cancels steady state errors caused by steps in $z(t)$ because $\lim_{s\to 0}(1 - e^{-\tau_0 s}) = 0$. Moreover, the time needed to remove disturbance effects (the settling time of disturbances defined as in the previous subsection) is approximately:

$$t_{sz} = 2\tau_0 + 3T_{10} \quad (13)$$

Then, the proposed compensation term is:

$$H(s) = \frac{(1 + T_{10}s)(1 + T_{20}s)}{K_0(1 + \mu s)^2}, \quad (14)$$

where factor $(1+ \mu s)^2$ has the same purpose as in (8). The resulting controller yields:

$$H(s) = \frac{(1 + 51.2s)(1 + 12.1s)}{3.66(0.5s + 1)^2}. \quad (15)$$

4.7. Comparison of the schemes

Responses and control signals of the four *SP* schemes to a unity step command $r(t)$ at t=0 s and to a step disturbance $z(t)$ of amplitude - 0.3 at t=400 s are shown in Fig. 5. This figure shows that the step command responses of the three schemes exhibit the same settling time t_s=171 s and overshoot M_p = 0.8%. However, they exhibit different responses to the step disturbance.

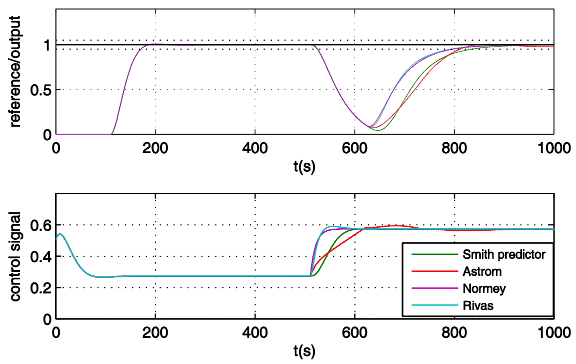

Fig. 5. Responses of the three SP control schemes.

Table II compares overshoot (or undershoot) and settling time of the disturbance responses of the four compared schemes. Note that variables of Fig. 5 are increments with respect to the equilibrium point and have been normalized for comparison purposes.

Table II. Features of the disturbance responses of the *SP* schemes.

	SP scheme	*Over/under shoot (% with respect to AK_0)*	*t_{sz} (s)*
(b)	Smith	86.2	446
(c)	Astrom	85.6	423
(d)	Normey-Rico	84.8	359
(e)	Rivas-Perez	84.9	353

The results show that Normey-Rico and Rivas-Perez schemes provide very similar disturbance rejections. However, Rivas-Perez scheme uses a lower order controller and simpler tuning rules than the Normey-Rico one.

4.7. Uniformity of the outlet temperature.

As it was mentioned in the Introduction a better behaviour on disturbances rejection implies a higher uniformity of the outlet temperature and, consequently, an energy saving in the process operation.

For illustrative purposes, this section shows a simulated scenario of intensive disturbances and the behaviour of the compared schemes.

Let's define the outlet temperature uniformity as its IAE index:

$$\delta = \int_0^t |r(\rho) - y(\rho)| d\rho. \quad (16)$$

where t is the simulation time.

Let's assume the disturbance scenario represented in Fig. 6 for nominal process and a fixed temperature set value of 390ºC.

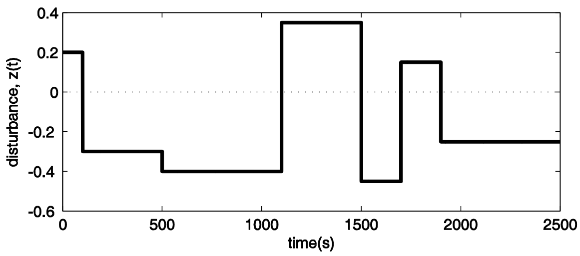

Fig. 6. Disturbances scenario.

Figure 7 represents the time response that the four *SP* schemes provide and Table III compares the IAE index, δ, of each scheme.

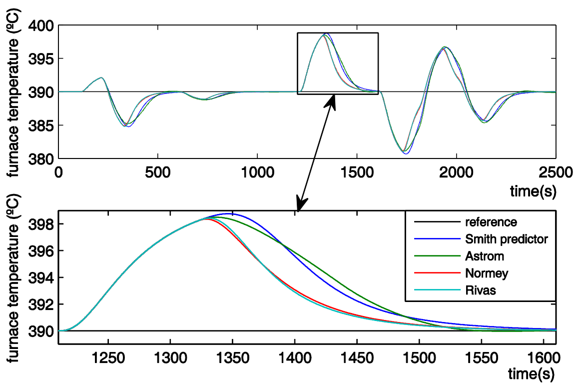

Fig. 7. Compared results

Table III. IAE index comparison for scenario shown in Fig. 6

	SP scheme	IAE index, δ
(a)	Smith	21133
(b)	Astrom	21357
(c)	Normey-Rico	17537
(d)	Rivas-Perez	17496

The results again show that Normey-Rico and Rivas-Perez schemes provide very similar disturbance rejections and, therefore, a similar outlet temperature uniformity. In fact, Rivas-Perez scheme provides slightly higher (lower IAE index) temperature uniformity than Normey-Rico scheme.

5. CONCLUSIONS

This paper has tackled the problem of controlling the outlet temperature of a crude oil preheating furnace. An identify-cation procedure using real time data of a furnace of Havana petroleum refinery has been carried out in order to obtain a linear model for its control. The resulting model is a second order plus time-delay one in which the time delay term is dominant, i.e much more significant than its time constants. Validation showed a good agreement between experimental and model based predicted data. Unmeasured disturbance effects have also been modelled by means of step commands passing through a filter which affects the input signal of the furnace.

Several Smith predictor based control schemes have been studied in order to substitute the standard *PI* controller at present used in this process. Comparison of simulated results showed that the modification of the *SP* scheme proposed by Rivas-Perez et al. (1987) yielded the best results in terms of step disturbance rejection (Fig. 5 and 7 and Tables II and III) providing higher outlet temperature uniformity. Although Rivas-Perez and Normey-Rico schemes provide quite similar results, the controller proposed by Rivas-Perez schemes is of lower order and its tuning method is simpler than the one proposed by Normey-Rico.

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