IFAC Conference on Advances in PID Control
PID'12
Brescia (Italy), March 28-30, 2012

Benchmark for PID control based on the Boiler Control Problem

F. Morilla

Departamento de Informática y Automática, Escuela Técnica Superior de Ingeniería Informática, UNED, C/. Juan del Rosal 16, 28040 Madrid, Spain, (Tel: 34+913987156; fmorilla@dia.uned.es)

Abstract: This paper describes the benchmark proposed for the IFAC Conference on Advances in PID Controllers (PID'12) at the end of july 2011. It is expected that this benchmark allows researchers to test their recent developments in the design of PID controllers. Two approaches to the boiling process were provided; the first ready to test a multivariable PID controller and the second ready to test PID controller, both with or without feedforward. Nevertheless, the boiler control systems described in this paper are ready to test other multivariable control strategies. The full documentation about the benchmark was linked from the website PID'12 and will remain in www.dia.uned.es/~fmorilla/benchmarkPID2012.

Keywords: boiler control, boiling process, decentralized control, PID control.

1. INTRODUCTION

Steam generation systems are a crucial part of most power plants. Therefore, boiler control is an important problem for power plants that are frequently changing load or subject to sudden load disturbances, which are common in current market driven electricity industry. In such circumstances it is required to keep the boiler operating well for large changes in the operating conditions. One way to achieve this is to incorporate more process knowledge into the control system (Aström and Bell, 2000).

In the boiler area, nowadays many models exist ranging from complex knowledge based models to experimental models derived from special plant tests. But, any model to be used for control system testing must take into account the coupling between the individual boiler subsystems. This is satisfied by the control oriented model proposed by Pellegrinetti and Bentsman (1996), that predicts the process response in terms of measurable outputs (drum pressure, drum water level, and excess oxygen in flue gas) to the major manipulated inputs (air/fuel flow rates, feedwater flow rate) as well as the effect of disturbances (changed steam demand, sensor noise), model uncertainty (e.g., fuel calorific value variations, heat transfer coefficient variations, distributed dynamics of the steam generation), and constraints (actuator constraints, unidirectional flow rates, drum flooding).

There is an extensive literature related with boiler control systems. Traditionally, they have been built up as combination of conventional single variable control loops, with or without feedforward, and computation of certain variables that cannot be measured directly (Balchen and Mummé, 1988). Other researchers propose to use advanced control techniques, because they may give better performance than a decentralized one (Tan et al. 2004, Lu et al. 2005, Garrido et. al. 2009). More complex techniques, LQG/LTR, H_∞ control, predictive control, and fuzzy control, have been also applied to improve boiler performance (Tan et al. 2005). The advantage of using PID controllers is their ease of implementation and tuning, while the advantage of other controllers is their performance improvement. There is always a tradeoff between ease to use and cost to implement and tune (Tan et al. 2004).

The benchmark proposed in this work will allow researchers to approach an important control problem in order to test their recent developments in the design of PID controllers. This paper is organized as follows. The Boiler Control Problem is presented in Section 2. The attention is first addressed to the most general problem, and then, it is addressed to the MIMO and SISO problems selected for the benchmark. In addition, details about the Boiler Model are given, paying special attention to the two open-loop boiling processes considered in the benchmark. Section 3 describes how the testing and comparative evaluation of multivariable PID controllers can be carried out. The Section 4 is dedicated to test the PID controller. Finally, section 5 summarizes the conclusions.

All the examples mentioned in this document can be checked downloading the files provided by the author in the website: www.dia.uned.es/~fmorilla/benchmarkPID2012/. Full documentation about the benchmark is also available in the website.

2. THE BOILER CONTROL PROBLEM

A schematic picture of a typical drum boiler is shown in Fig. 1. The water that is to be evaporated is added to a drum. From the drum, the water goes down through the downcomers, which are located outside of the firebox. The water then goes into the risers, which are located in the hottest part of the furnace. Here, the water evaporates, and the steam rises and flows back up to the drum. The combustible, fuel in this case, is burned with air in the firebox.

The function of a boiler is to deliver steam of a given quality (temperature and pressure) either to a single user, such as a steam turbine, or to a network of many users. Then, a properly functioning boiler must satisfy the following basic requirements:

1) The ratio of air to fuel must be carefully controlled in order to obtain good, safe, and efficient combustion.

2) The level of water in the drum must be controlled at the desired level in order to prevent overheating of drum components or flooding of steam lines.

3) A desired steam pressure must be maintained at the outlet of the drum despite variations in the quantity of steam demanded by users.

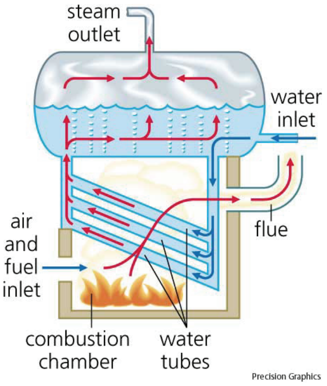

Fig. 1. Schematic picture of an industrial drum boiler.

To fulfil the control objectives listed above, the control system for a drum boiler is usually divided into several subsystems. Therefore, assuming that air flow rate is regulated properly by the air control subsystem, we can approach the boiling process as the 3x3 system shown in Fig. 2. In this system, two variables (steam pressure and water level) can be controlled by two manipulated variables (fuel flow and water flow) taking into account the measured disturbance variable (load level). In addition, the indirect controlled variable (oxygen level) can be used as quality performance variable.

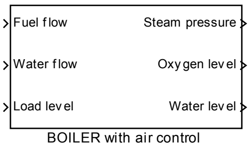

Fig. 2. Boiling process approached as a 3x3 system.

Moreover, assuming that the water flow rate is regulated properly by the feedwater control subsystem, we can approach the boiling process as the 2x3 system shown in Fig. 3. Now the steam pressure can be controlled by the fuel flow taking into account the load level, and the indirect controlled variable (oxygen level) and the controlled variable (water level) can be used as quality performance variables.

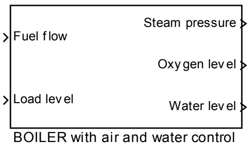

Fig. 3. Boiling process approached as a 2x3 system.

With the previous assumptions, the Benchmark provides two boiler control systems. The system of Fig. 4, that is ready to test a multivariable PID Controller with or without feedforward. And the system of Fig. 5, that is ready to test a PID Controller with or without feedforward. Nevertheless, any type of controller can be tested.

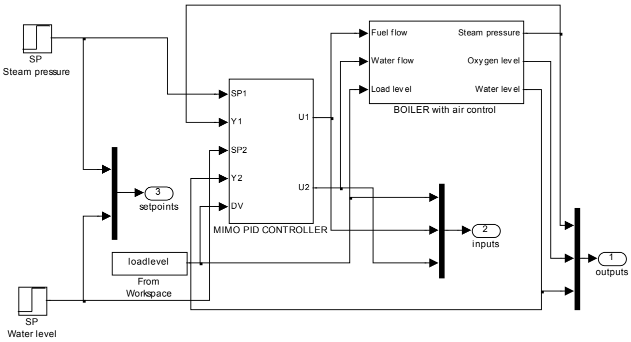

Fig. 4. MIMO PID Boiler Control System.

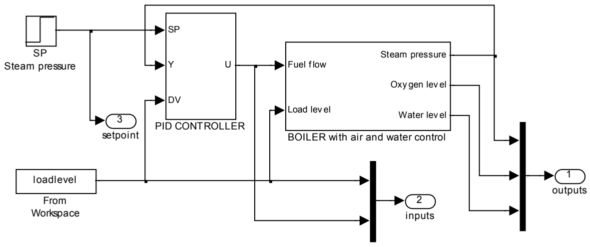

Fig. 5. SISO PID Boiler Control System.

2.1 *About the controllers*

The multivariable controller needs to be a 5x2 Simulink block; however, it could be a continuous, a discrete or a hybrid block. There is also total freedom to decide the structure of the block; the controller can use the five input signals or only some of them. The five input signals are: the steam pressure (Y1), its setpoint (SP1), the water level (Y2), its setpoint (SP2) and the load level (DV). The two output signals are the fuel flow (U1) and the water flow (U2). Fig. 6 shows the multivariable controller included by default in the Benchmark. It is a decentralized PID controller, the simplest structure, with two discrete PID controllers (PID1 and PID2) without feedforward compensation.

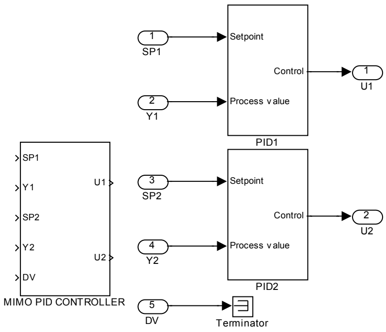

Fig. 6. The decentralized PID controller included by default in the MIMO PID Boiler Control System.

The PID controller needs to be a 3x1 Simulink block; however, it could be a continuous, a discrete or a hybrid block. There is also total freedom to decide the structure of the block; the controller can use the three input signals or only some of them. The three input signals are: the steam pressure (Y), its setpoint (SP) and the load level (DV). The output signal is the fuel flow (U). Fig. 7 shows the PID controller included by default in the benchmark.

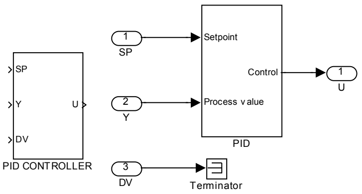

Fig. 7. The PID controller included by default in the SISO PID Boiler Control System.

2.2 *About the Boiler Model*

The control systems of Fig. 4 and 5 use the same nonlinear model proposed by Pellegrinetti and Bentsman (1998). The model has been developed in Simulink including some changes: several coefficients have been slightly modified, restricted ranges for the inputs and outputs have been selected and normalized in percentage. However, the following main features of the model have been preserved:

1) It has a relatively low complexity while faithfully capturing the essential plant dynamics and its nonlinearities over a wide operating range.

2) The model is control oriented in that the manipulated variables, the controlled variables and the significant disturbance are explicitly shown.

3) The model is realistic in that the constraints on the manipulated variables are known, and the measurement noise and time delays are present on the outputs.

The boiler model accepts input variables in the range 0-100%. And additionally, a rate limit of ±1%/s has been incorporated for the fuel flow and indirectly for the air flow. The model is ready to be controlled with a sampling period greater than 0.2 s, starting always in the same operating point given by: Fuel flow≅35.21%, Water flow≅57.57%, Load level≅46.36%, Steam pressure=60%, Oxygen level=50%, Water level=50%.

The open-loop features of the 3x3 boiling process are the following: The steam pressure response is stable for the three inputs (the two flows and the load level). The oxygen level is only slightly affected by the fuel flow. The water level in the drum shows non-minimum phase behaviour for the fuel flow and the load level, in addition to an integrating response for the three inputs. The time delays are not significant in this process. The main control difficulties in this multivariable process are caused by the coupling, the non-minimum phase, the integration and the load disturbance. More information about the boiling process is available in the benchmark website.

The open-loop features of the 2x3 boiling process are the following: the steam pressure response is stable for the two inputs. The oxygen level is only slightly affected by the fuel flow. The water level in the drum shows now the self-regulating behaviour for the two inputs. The level control loop is hiding some difficulties mentioned before, but they are present because the process is the same.

3. TESTING MULTIVARIABLE PID CONTROLLERS

The MIMO PID Boiler Control System of Fig. 4 is ready to test any multivariable controller operating the boiler in different scenarios. The Matlab program *Test_Boiler_MIMOControl.m* is provided to help this testing. The only requirement is that all experiments should start from the same operating point mentioned in Section 2.2. They can include step changes in the steam pressure setpoint, in the water level setpoint and time variant load level conditions.

Three types of experiments have been considered in the benchmark. The standard experiment including a step change in the load level, the experiment type 1 including a profile of load level, and the experiment type 2 including a single step in the steam pressure setpoint. The MAT-files *dat_in_boiler_mimo*, *dat_in_boiler_mimo1* and *dat_in_boiler_mimo2* are prepared to generate the corresponding simulation conditions. These experiments or any others experiments can be also used to explore the boiler operating points. The model is able to attend load level between 20% and 70% with steam pressures between 20% and 70%.

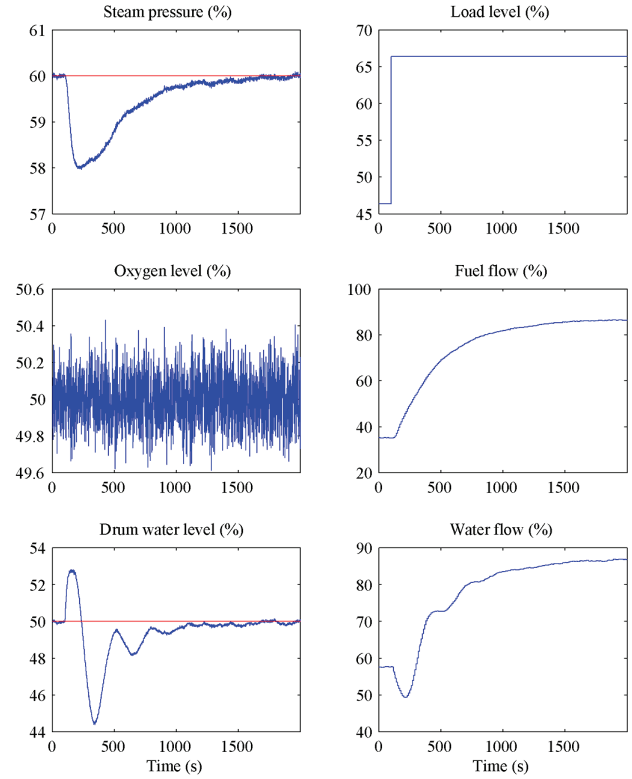

Fig. 8. Example of standard test with the MIMO PID Boiler Control System.

Fig. 8 is an example of standard test. A new operating point has been reached due to a 20% load level step change at t=100 s. It has been possible increasing the fuel flow and the water flow, while the steam pressure and the water level recover their setpoints after about 1800 s. During the experiment the oxygen level remains indirectly controlled by the fuel/air ratio, affected only by the noise. This example can be checked with the m-file *Test_Boiler_MIMOControl* loading the MAT-file *dat_in_boiler_mimo*.

The benchmark aims also to facilitate the comparative evaluation of controllers providing the Matlab program *Boiler_MIMOControl_Evaluation.m*. Two controllers, which have been previously tested in the same experiment, can be compared each time. One of them plays the role of controller of reference (C_r) and the other one plays the role of controller to evaluate (C_e). For the multivariable boiler control problem seven individual performance indexes and one combined index have been proposed in the comparative evaluation.

The first three indexes are the Ratios of Integrated Absolute Error (RIAE) taking into account that the steam pressure and the water level have their respective setpoints and that the oxygen level must remain in the 50%. The fourth and fifth indexes are the Ratios of Integrated Time multiplied Absolute Error (RITAE) for the two controlled variables, the steam pressure and the water level. The variable typechange is used to display the RITAE index only when the respective setpoint has changed. The sixth and seventh indexes are the Ratios of Integrated Absolute Variation of Control signal (RIAVU) for the two manipulated variables, the fuel flow and the water flow. The combined index J_M is obtained as the mean value of the seven individual indexes using a weighting factor (w) for the RIAVU indexes. The following expressions, which summarize these indexes, have been programmed in the Matlab function *JBoilerMIMO.p*.

$$\mathrm{IAE}_i = \int_0^{\mathrm{time}} \left|e_i(t)\right| \, dt \tag{1}$$

$$\mathrm{ITAE}_i = \int_{\mathrm{tchange}}^{\mathrm{time}} (t-\mathrm{tchange}) \left|e_i(t)\right| \, dt \tag{2}$$

$$\mathrm{IAVU}_i = \int_0^{\mathrm{time}} \left|\frac{d\,u_i(t)}{dt}\right| dt \tag{3}$$

$$\mathrm{RIAE}_i(C_e,C_r) = \frac{\mathrm{IAE}_i(C_e)}{\mathrm{IAE}_i(C_r)} \tag{4}$$

$$\mathrm{RITAE}_i(C_e,C_r) = \mathrm{typechange}_i \frac{\mathrm{ITAE}_i(C_e)}{\mathrm{ITAE}_i(C_r)} \tag{5}$$

$$\mathrm{RIAVU}_i(C_e,C_r) = \frac{\mathrm{IAVU}_i(C_e)}{\mathrm{IAVU}_i(C_r)} \tag{6}$$

$$J_M(C_e,C_r,w) = \frac{\sum_{i=1}^{3}\mathrm{RIAE}_i(C_e,C_r) + \mathrm{RITAE}_1(C_e,C_r) + \mathrm{RITAE}_3(C_e,C_r) + \sum_{i=1}^{2} w\ \mathrm{RIAVU}_i(C_e,C_r)}{3 + \mathrm{typechange}_1 + \mathrm{typechange}_3 + 2\,w} \tag{7}$$

Note that the comparative evaluations are not restricted to very different controllers. For instance, the comparative evaluations of controllers which only differ in the control parameters can be useful to find the best tuning. The Table 1 shows two decentralized PID controllers that are candidates for the next comparative evaluations. The table only shows the control parameters that have been modified: the sampling period for control t_c, the proportional gain (K_P) and the integral time (T_I). The other common features are: no derivative action (T_D=0), proportional action with the error signal, 0-100% control range, 1%/s rate limit in controller 1.

Table 1. Decentralized PID controllers for the next comparative evaluations

		t_c	K_P	T_I
Case of reference	Controller 1	10 s	2.5	50 s
	Controller 2	10 s	1.25	50 s
Case to evaluate	Controller 1	5 s	5.0	25 s
	Controller 2	5 s	2.5	25 s

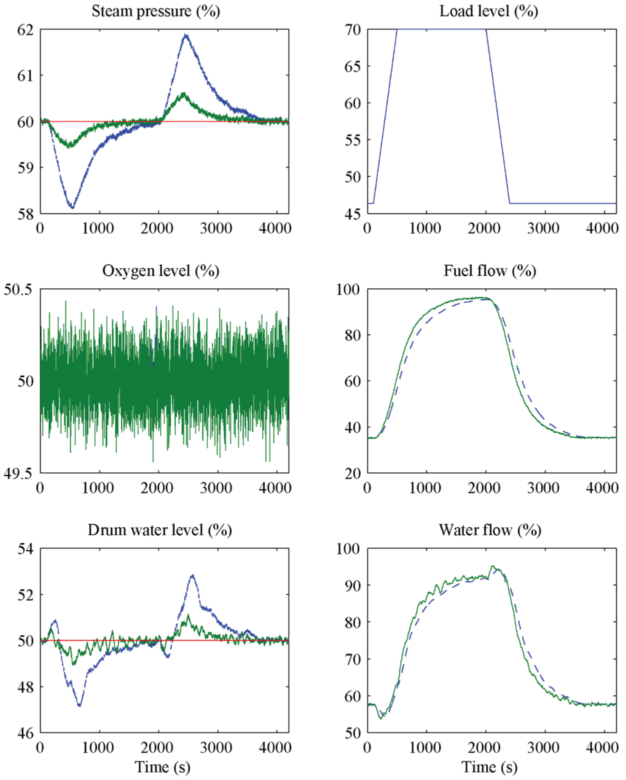

Fig. 9. Example of comparative test type 1 for the MIMO PID controllers of Table 1. Case of reference in blue. Case to evaluate in green.

Fig. 9 is an example of comparative test type 1 for the controllers of Table 1. Starting at the operating point, the system had to attend a time variant load level. First, the load increased in ramp from 46.36% at t=100 s until 70% in t=500 s; second, the load remained constant; third, the load decreased in ramp at t=2000 s until reaching the initial operating point at t=2400 s, where it remained until t=4200 s. The change of control parameters has brought two direct benefits: the steam pressure and the water level show minor deviations from their setpoints. However, that was possible with more activity in the fuel flow and the water flow. During the experiment the oxygen level remains indirectly controlled by the fuel/air ratio, affected only by the noise. The Table 2 shows the numerical comparative evaluation. The change of control parameters has drastically reduced the error indexes RIAE1 and RIAE3. It comes at the expense of increasing the control indexes RIAVU1 and RIAVU2. The global benefit is apparent by a J_M index less than the unit, from 0.5261 with w=0 to 0.9574 with w=1. The value 0.68 corresponds to w=0.25. This example can be checked with the m-file *Boiler_MIMOControl_Evaluation* loading the MAT-files *test1BoilerMIMO_CL1* and *test1BoilerMIMO_CL2*.

Table 2. Indexes corresponding to the test of Fig. 9

$RIAE_1$	$RIAE_2$	$RIAE_3$	$RITAE_1$
0.2645	0.9996	0.3142	-
$RITAE_3$	$RIAVU_1$	$RIAVU_2$	$J_M(0.25)$
-	1.5218	1.6868	0.6801

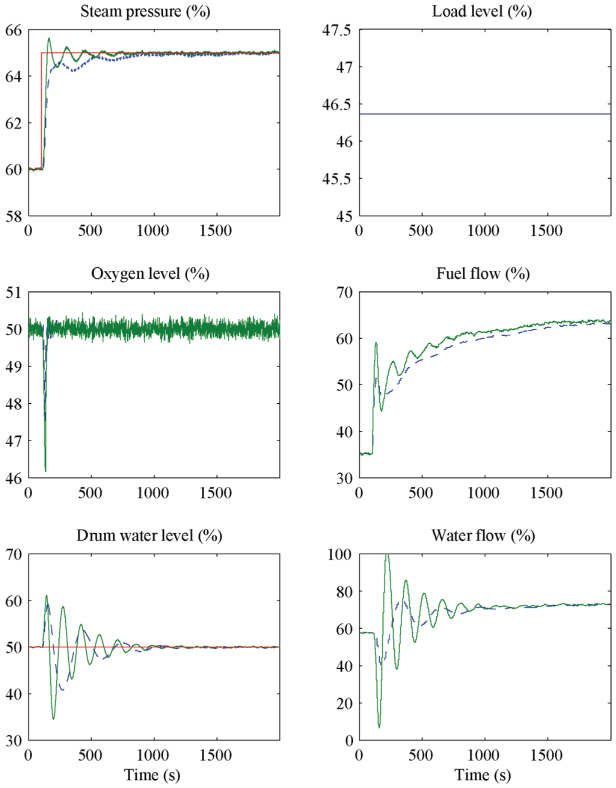

Fig. 10. Example of comparative test type 2 for the MIMO PID controllers of Table 1. Case of reference in blue. Case to evaluate in green.

Fig. 10 is an example of comparative test type 2 for the same decentralized PID controllers. Starting at the operating point, the system had to attend a sudden change of 5% in the steam pressure setpoint at t=100 s. The change of control parameters has brought only benefits about the steam pressure response. The water level showed great oscillations and there was more activity in the fuel flow and the water flow. During the experiment, the oxygen level showed a greater transitory deviation. The Table 3 shows the numerical comparative evaluation. The change of control parameters has drastically reduced the error indexes RIAE1 and RITAE1. It comes at the expense of increasing the other indexes. There is not apparent global benefit, because the J_M index goes from 0.7936 with w=0 to 1.7082 with w=1. The table shows that J_M is near the unit for w=0.25. This example can be checked with the m-file *Boiler_MIMOControl_Evaluation* loading the MAT-files *test2BoilerMIMO_CL1* and *test2BoilerMIMO_CL2*.

Table 3. Indexes corresponding to the test of Fig. 10

$RIAE_1$	$RIAE_2$	$RIAE_3$	$RITAE_1$
0.5210	1.1540	1.1298	0.3696
$RITAE_3$	$RIAVU_1$	$RIAVU_2$	$J_M(0.25)$
-	2.6260	4.4489	1.0985

4. TESTING THE PID CONTROLLER

The SISO PID Boiler Control System of Fig. 5 is prepared to test any controller for step change in the steam pressure setpoint and for time variant load level conditions. The procedure to follow is similar to the multivariable case and three types of experiments have been considered. For the single-loop boiler control problem, five individual indexes and one combined index have been proposed in order to compare the controllers. The Matlab program *Boiler_SISOControl_Evaluation.m* and the function *JBoilerSISO.p* are provided to help this testing. The combined index is given now by (8).

$$J_S\left(C_e,C_c,w\right) = \frac{\sum_{i=1}^{3} RIAE_i(C_e,C_r) + RITAE_1(C_e,C_r) + w\ RIAVU(C_e,C_r)}{3 + typechange + w} \quad (8)$$

Table 4 shows the two PID controllers that are candidates for the next comparative evaluation. The table only shows the control parameters that have been modified: the sampling period for control t_c, the proportional gain (K_P) and the integral time (T_I). Others common features are: no derivative action (T_D=0), proportional action with the error signal, 0-100% control range, 1%/s rate limit in the controller.

Table 4. PID controllers for the next comparative evaluations

	t_c	K_P	T_I
Case of reference	10 s	2.5	50 s
Case to evaluate	5 s	5.0	25 s

Fig. 11 is an example of comparative test type 1 with the controllers of Table 4. The change of control parameters has brought a direct benefit: the steam pressure show minor deviations from its setpoint. Nevertheless that was possible with more activity in the fuel flow. During the experiment, the water level showed similar deviations and the oxygen level remained indirectly controlled by the fuel/air ratio, affected only by the noise. The Table 5 shows the numerical comparative evaluation. The change of control parameters has drastically reduced the error index RIAE1. It comes at the expense of increase the control index RIAVU. The global benefit is apparent by a J index less than the unit. The value 0.8370 corresponds to a weighting factor w=0.25. This example can be checked with the m-file *Boiler_SISOControl_Evaluation* loading the MAT-files *test1BoilerSISO_CL1* and *test1BoilerSISO_CL2*.

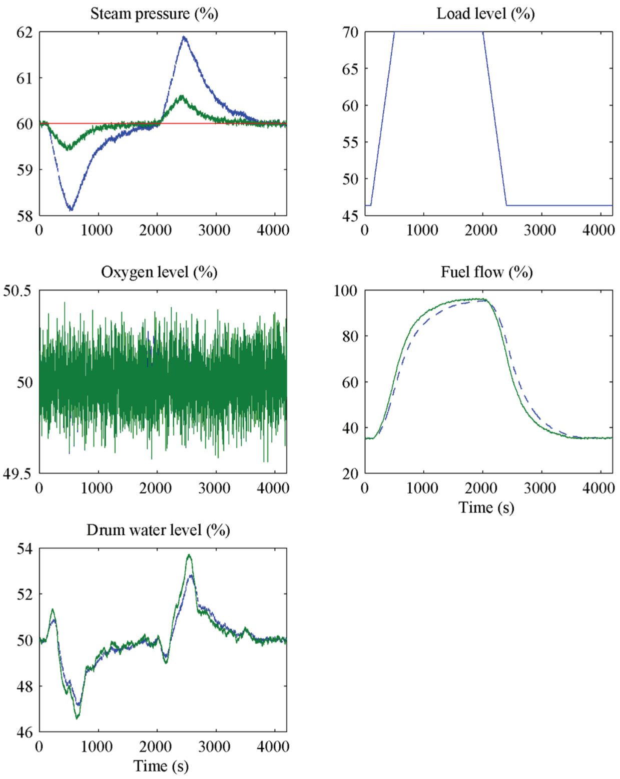

Fig. 11. Example of comparative test type 1 for the PID controllers of Table 4. Case of reference in blue. Case to evaluate in green.

Table 5. Indexes corresponding to the test of Fig. 11

RIAE$_1$	RIAE$_2$	RIAE$_3$	RITAE$_1$	RIAVU	$J_S(0.25)$
0.2646	1.0003	1.0747	-	1.5224	0.8370

Fig. 12 is an example of comparative test type 2, where the two PID controllers have the same K_P=5 and T_I=25 s, and different sampling periods; t_{c1}=10 s and t_{c2}=5 s respectively. The change of the sampling period has brought great benefits. The oscillations in the steam pressure response have almost disappeared. The Table 6 shows that all indexes have been drastically reduced. This example can be checked with the m-file *Boiler_SISOControl_Evaluation* loading the MAT-files *test2BoilerSISO_CL1* and *test2BoilerSISO_CL2*.

Table 6. Indexes corresponding to the test of Fig. 12

RIAE$_1$	RIAE$_2$	RIAE$_3$	RITAE$_1$	RIAVU	$J_S(0.25)$
0.5043	0.6912	0.7939	0.6355	0.5745	0.6514

5. CONCLUSIONS

The benchmark provides two approaches to the boiling process in order that researchers can test their recent developments in the design of PID controllers. It provides also individual and combined performance indexes for using in the comparative evaluation of controllers. Three types of experiments are used to illustrate the decentralized or single-loop PI control of the boiling process. Nevertheless, the benchmark can be very useful to test any multivariable controller, including or not PID controllers, operating the boiler in different scenarios.

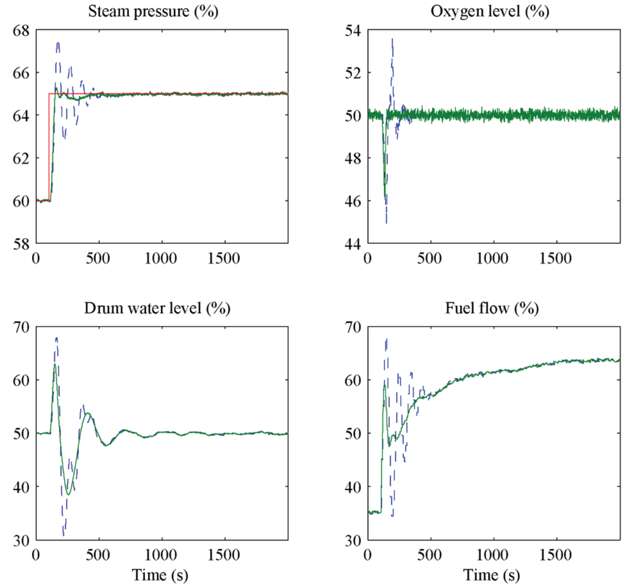

Fig. 12. Example of comparative test type 2 for two PID controllers with different sampling period. Case of reference in blue. Case to evaluate in green.

ACKNOWLEDGEMENTS

This work was supported by the Spanish CICYT under grant DPI 2007-62052. The author wishes to express his gratitude for the support and suggestions during the preparation of the benchmark to R. González from Petronor, F. Vazquez and J. Garrido from University of Córdoba, S. Dormido from UNED, and A. Visioli from University of Brescia.

REFERENCES

Aström K. J., and Bell, R. D. (2000). Drum-boiler dynamics. *Automatica*, Vol. 36, pp. 363-378.

Balchen, J. G., and Mummé, K. I. (1988). *Process Control: Structures and Applications*. Van Nostrand Reinhold Company Inc., NewYork.

Garrido, J., Morilla, F., and Vázquez, F. (2009). Centralized PID Control by Decoupling of a Boiler-Turbine Unit. 10th European Control Conference, Budapest.

Lu, C. X., Rees, N. W., and Donaldson, S. C. (2005). The use of the Aström-Bell model for the design of drum level controllers in power plant boilers. 16th IFAC World Congress, Prague.

Pellegrinetti, G., and Bentsman, J. (1996). Nonlinear Control Oriented Boiler Modelling - A Benchmark Problem for Controller Design. *IEEE Transactions on Control Systems Technology*, Vol. 4, No. 1, pp 57-64.

Tan, W., Liu, J., Fang, F., and Chen, Y (2004). Tuning of PID controllers for boiler-turbine units. *ISA Transactions* Vol. 43, pp. 571–583.

Tan, W., Marquez, H. J., Chen, T., and Liu, J. (2005). Analysis and control of a nonlinear boiler-turbine unit. *Journal of Process Control*. Vol. 15, No. 8, pp. 883-891.