BENCHMARK PID 2012

Benchmark for PID control based on the Boiler Control Problem

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1. INTRODUCTION

The 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, many models now 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. All this is satisfied by the control oriented model proposed by Pellegrinetti and Bentsman (1998), that predicts process response in terms of measurable outputs (drum pressure, drum water level, and excess oxygen in flue gas) to the major controllable 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 o 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 use 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 PID 2012 allows researchers to approach an important control problem in order to test their recent developments in the design of PID controllers. This document 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 PID 2012. Also details about the Boiler Model are given, with special mention to the open-loop boiling processes considered in the Benchmark PID 2012. 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. All the examples mentioned in this document can be checked uploading the files provided by the author in the website: http://www.dia.uned.es/~fmorilla/benchmarkPID2012/. In the website you can get also a full documentation about the benchmark.

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 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.

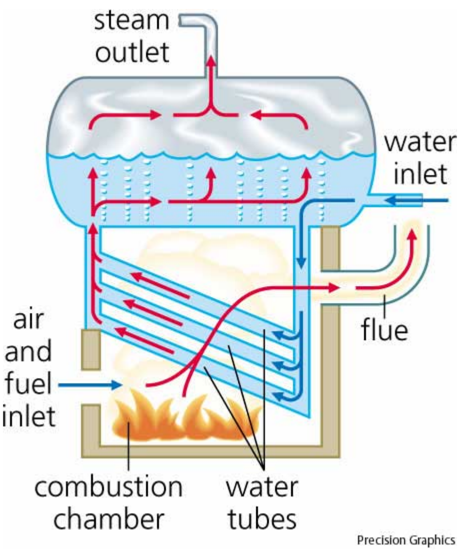


Fig. 1. Schematic picture of an industrial drum boiler.

To fulfill the control objectives listed above, the control system for a drum boiler is usually divided into several subsystems. Therefore, assuming air flow rate is regulated well by the air control subsystem, we can approach the boiling process as the 3x3 system shown in Fig. 2. Where, 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). And where, the indirect controlled variable (oxygen level) can be used as quality performance variable.

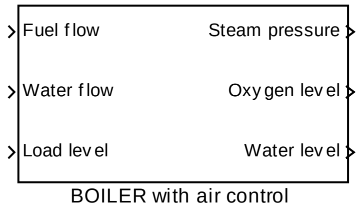


Fig. 2. Boiling process approached as a 3x3 system.

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

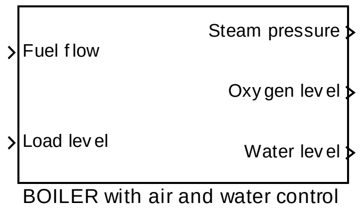


Fig. 3. Boiling process approached as a 2x3 system.

With the previous assumptions the Benchmark PID 2012 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 could be tested.

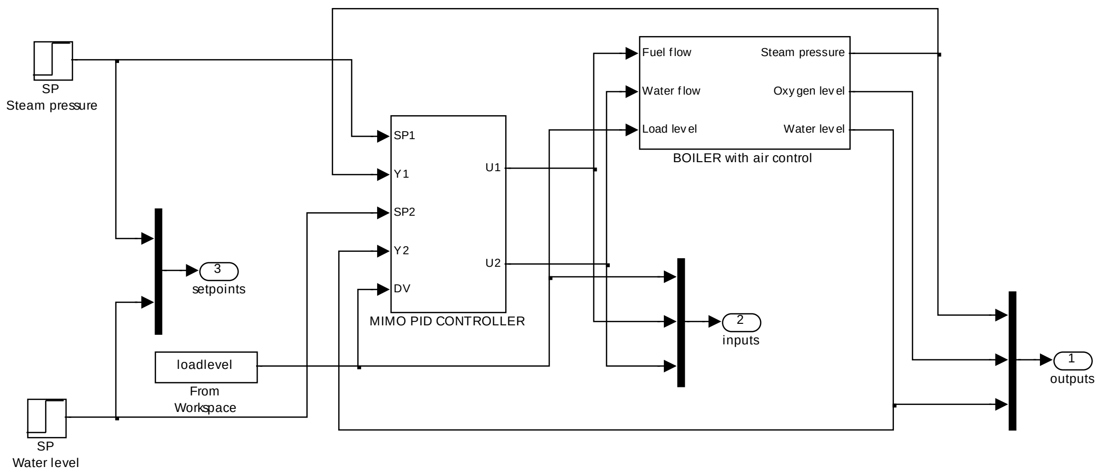


Fig. 4. MIMO PID Boiler Control System.

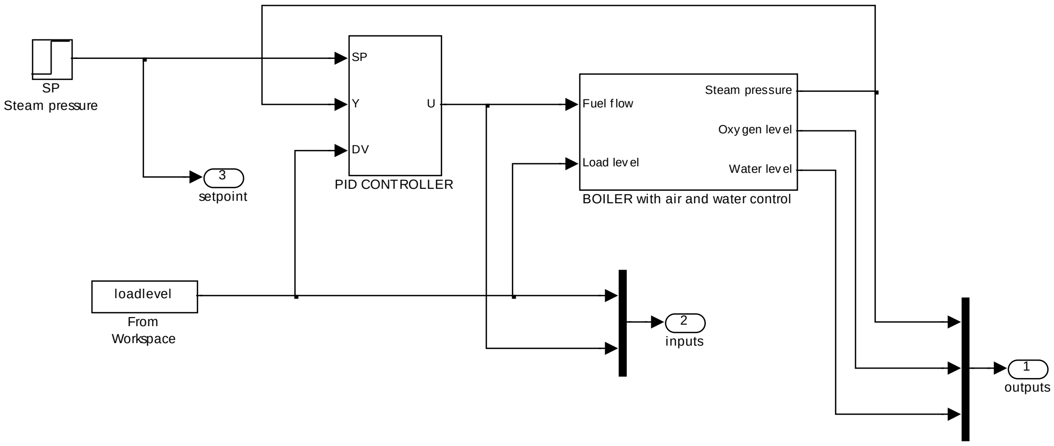


Fig. 5. SISO PID Boiler Control System.

2.1 About the controllers

The multivariable controller needs to be a 5x2 Simulink block, but 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 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 PID 2012. It is a decentralized PID controller, the simpler structure, with two PID discrete controllers (PID1 and PID2) without feedforward compensation.

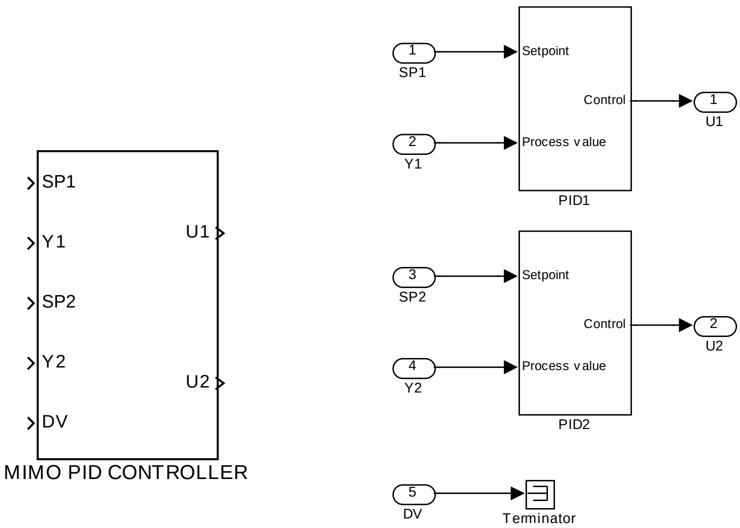


Fig. 6. The decentralized PID controller included by default in the MIMO PID Boiler Control System.

The PID controller needs to be a 3x1 Simulink block, but 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 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 PID 2012.

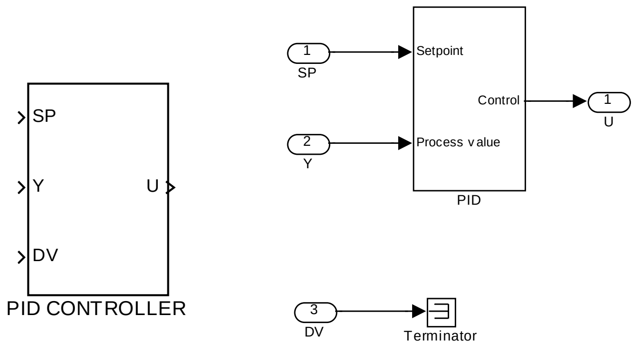


Fig. 7. The PID controller included by default in the SISO PID Boiler Control System.

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%. But 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 evident in the step-test shown in Fig. 8. In short, 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 level of water 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.

The open-loop features of the 2x3 boiling process are evident in the step-test shown in Fig. 9. In short, the steam pressure response is stable for the two inputs. The oxygen level is only slightly affected by the fuel flow. The level of water 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.

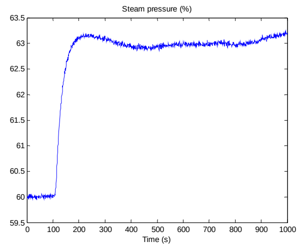
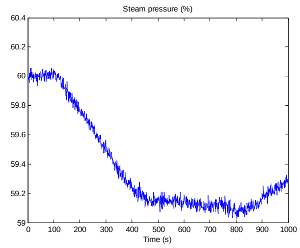
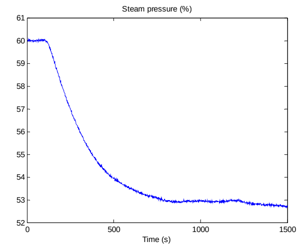
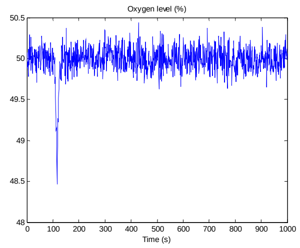
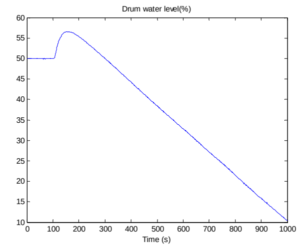
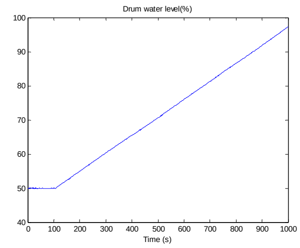
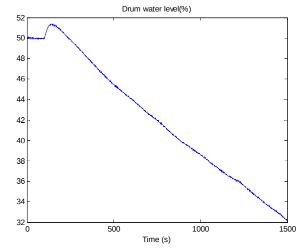
<table>
<tr><td>Step change of 10% in fuel flow at t=100 s</td><td>Step change in water flow of 5% at t=100 s</td><td>Step change of 10% in load level at t=100 s</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td></td><td>The oxygen level it is not affected by this change.</td><td>The oxygen level it is not affected by this change.</td></tr>
<tr><td></td><td></td><td></td></tr>
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Fig. 8. A step-test of the 3x3 boiling process.

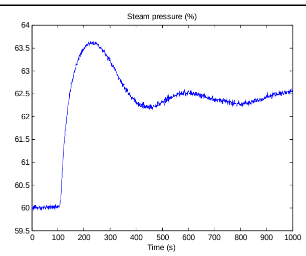
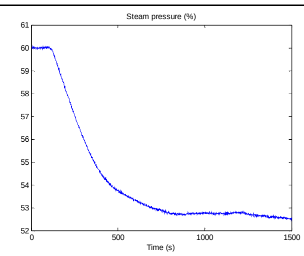
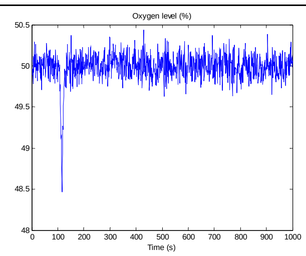
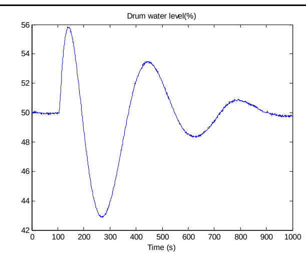
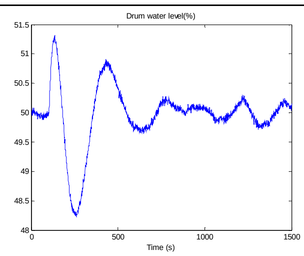
<table>
<tr><td>Step change of 10% in fuel flow at t=100 s</td><td>Step change of 10% in load level at t=100 s</td></tr>
<tr><td></td><td></td></tr>
<tr><td></td><td>The oxygen level it is not affected by this change.</td></tr>
<tr><td></td><td></td></tr>
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Fig. 9. A step-test of the 2x3 boiling process.

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 PID 2012. 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 files dat_in_boiler_mimo.mat, dat_in_boiler_mimo1.mat and dat_in_boiler_mimo2.mat 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 20º and 70º with steam pressures between 20º and 70º.

The Fig. 10 is an example of standard test. A new operating point has been reached due to a 20% step load level 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 in 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 program Test_Boiler_MIMOControl.m loading the file dat_in_boiler_mimo.mat.

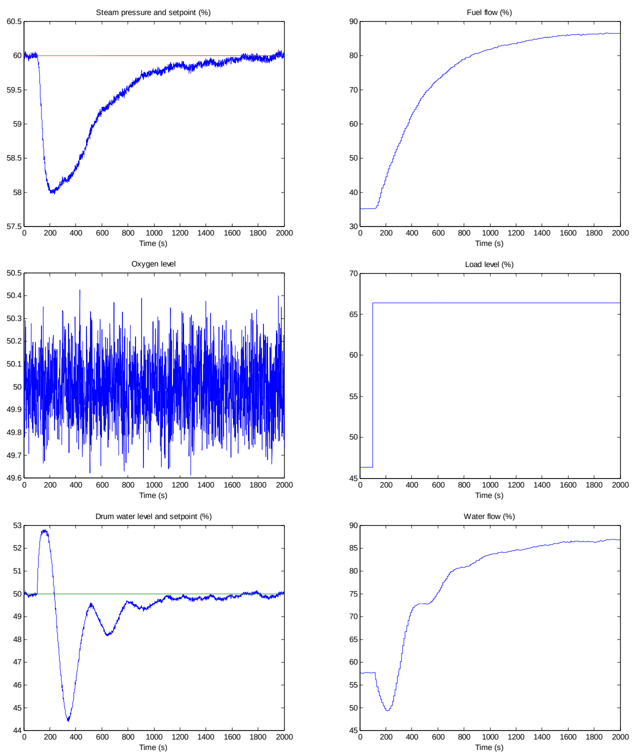

Fig. 10. Example of standard test with the MIMO PID Boiler Control System.

The Benchmark PID 2012 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 and the other one plays the role of controller to evaluate. 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 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 JBoilerMIMO.p.

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

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

$$\mathrm{IAVU}_i = \int_0^{\mathrm{time}} \left|\frac{d\, u_i(t)}{dt}\right| \, dt \tag{4}$$

$$\mathrm{RIAE}_i(C_c,C_r) = \frac{\mathrm{IAE}_i(C_c)}{\mathrm{IAE}_i(C_r)} \tag{5}$$

$$\mathrm{RITAE}_i(C_c,C_r) = \mathrm{typechange}_i \, \frac{\mathrm{ITAE}_i(C_c)}{\mathrm{ITAE}_i(C_r)} \tag{6}$$

$$\mathrm{RIAVU}_i(C_c,C_r) = \frac{\mathrm{IAVU}_i(C_c)}{\mathrm{IAVU}_i(C_r)} \tag{7}$$

$$J_M\left(C_c,C_c,w\right) = \frac{\sum_{i=1}^{3} \mathrm{RIAE}_i(C_c,C_r) + \mathrm{RITAE}_1(C_c,C_r) + \mathrm{RITAE}_3(C_c,C_r) + \sum_{i=1}^{2} w \;\; \mathrm{RIAVU}_i(C_c,C_r)}{3 + \mathrm{typechange}_1 + \mathrm{typechange}_3 + 2\,w} \tag{8}$$

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 tune. The Table 1 shows two decentralized PID controllers 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 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 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

The Fig. 11 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 t=100 s until reach the 70% in t=500 s, second the load remained constant, third the load decreased in ramp from t=2000 s until reach the initial operating point in 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. But 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 $RIAE_1$ and $RIAE_3$. It comes at the expense of increase the control indexes $RIAVU_1$ and $RIAVU_2$. The global benefit is apparent by a J_M index less than the unit. The value 0.68 corresponds to a weighting factor w=0.25. This example can be checked with the program Boiler_MIMOControl_Evaluation.m loading the files test1BoilerMIMO_CL1.mat y test1BoilerMIMO_CL2.mat.

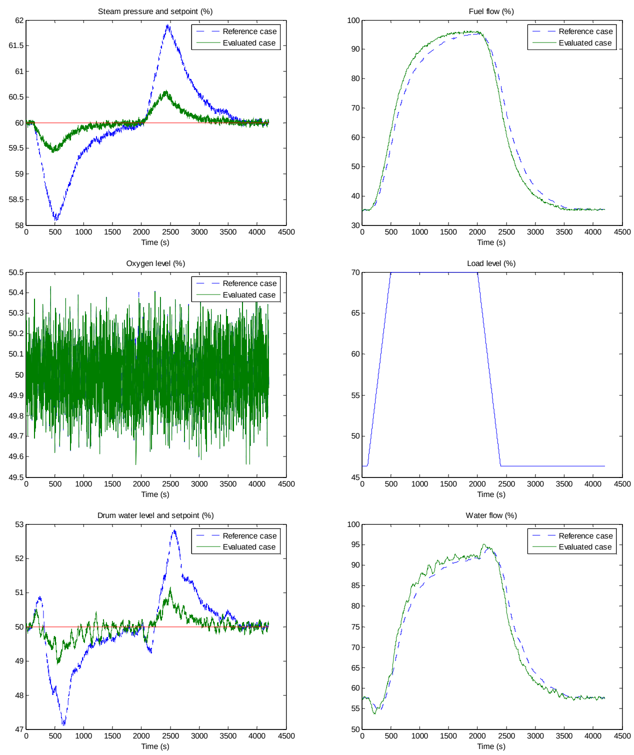

Fig. 11. Example of comparative test type 1 for the MIMO PID controllers of Table 1.

Table 2. Evaluation indexes corresponding to the test of Fig. 11

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

The Fig. 12 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 bigger transitory deviation. The Table 3 shows the numerical comparative evaluation. The change of control parameters has drastically reduced the error indexes $RIAE_1$ and $RITAE_1$. It comes at the expense of increase the other indexes. There is not apparent global benefit, because the J_M index corresponding to a weighting factor w=0.25 is near the unit. This example can be checked with the program Boiler_MIMOControl_Evaluation.m loading the files test2BoilerMIMO_CL1.mat y test2BoilerMIMO_CL2.mat.

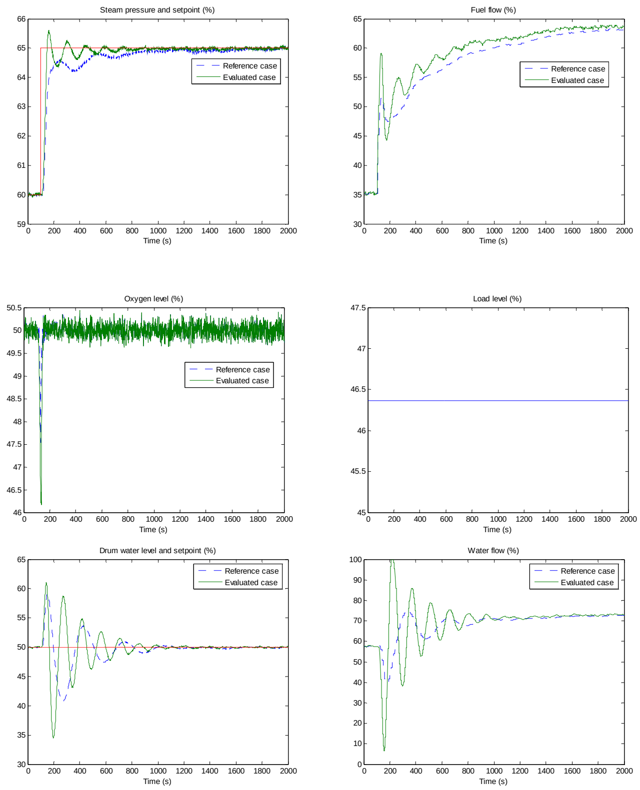

Fig. 12. Example of comparative test type 2 for the MIMO PID controllers of Table 1.

Table 3. Evaluation indexes corresponding to the test of Fig. 12

$RIAE_1$	$RIAE_2$	$RIAE_3$	$RITAE_1$	$RITAE_3$	$RIAVU_1$	$RIAVU_2$	$J_M(0.25)$
0.5210	1.1540	1.1298	0.3696	-	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 (9).

$$J_S\left(C_c,C_c,w\right) = \frac{\sum_{i=1}^{3} RIAE_i(C_c,C_r) + RITAE_1(C_c,C_r) + w\ RIAVU(C_c,C_r)}{3 + \text{typechange} + w} \qquad (9)$$

The Table 4 shows two PID controllers 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

The Fig. 13 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. But that was possible with more activity in the fuel flow. During the experiment the water level showed similar deviations and the oxygen level remains 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 $RIAE_1$. 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 program Boiler_SISOControl_Evaluation.m loading the files test1BoilerSISO_CL1.mat y test1BoilerSISO_CL2.mat.

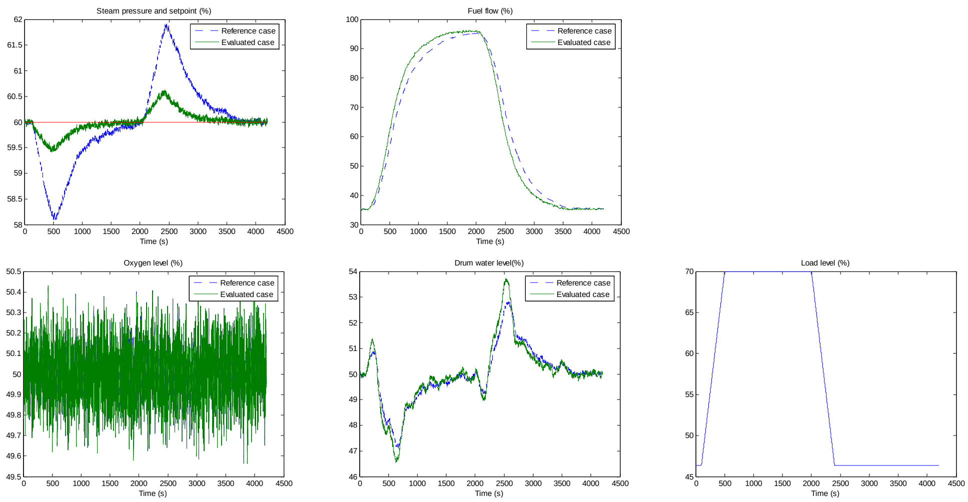

Fig. 13. Example of comparative test type 1 for the PID controllers of Table 4.

Table 5. Evaluation indexes corresponding to the test of Fig. 13

$RIAE_1$	$RIAE_2$	$RIAE_3$	$RITAE_1$	RIAVU	$J_S(0.25)$
0.2646	1.0003	1.0747	-	1.5224	0.8370

The Fig. 14 is an example of comparative test type 2, where the two PID controllers have the same K_P=5 and T_I=25 s, but 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 been almost disappeared. The Table 6 shows that all indexes have been drastically reduced. This example can be checked with the program Boiler_SISOControl_Evaluation.m loading the files test2BoilerSISO_CL1.mat y test2BoilerSISO_CL2.mat.

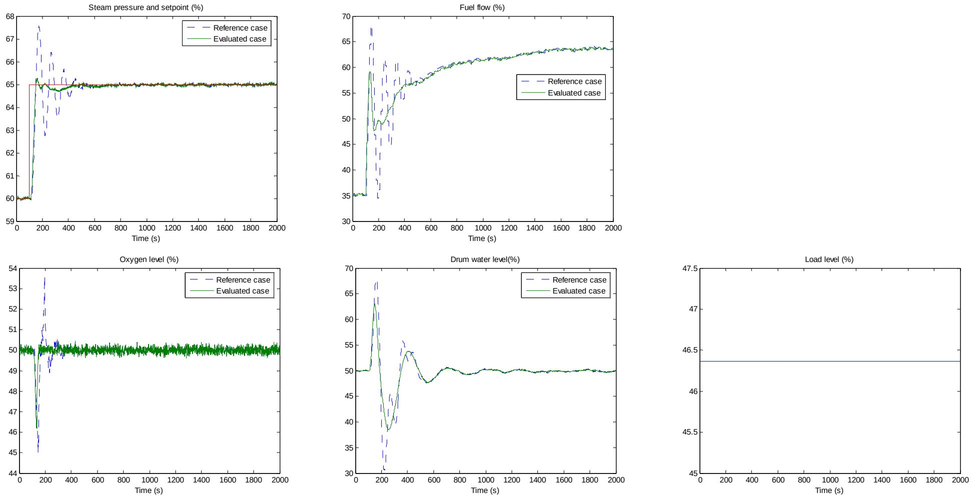

Fig. 14. Example of comparative test type 2 for two PID controllers with different sampling period.

Table 6. Evaluation indexes corresponding to the test of Fig. 14

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

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