MELiSSA

TECHNICAL NOTE

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TECHNICAL NOTE 83.7

Expertise of level 0 control loops on the 100 L pilot reactor

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Reference/Référence	ESA/ESTEC contract 19304/05/NL/CP
Issue/Edition	1
Revision/Révision	1
Date of issue/Date d'édition	March 07
Status/Statut	Draft

APPROVAL

Title *Titre*		Issue *Edition*	1	Revision *Révision*	1

Author *Auteur*	Jean-Luc Estival, Olivier Gerbi	Date *Date*	20/03/07

Approved by *Approuvé par*		Date *Date*	

CHANGE LOG

Reason for change	Issue/*Edition*	Revision/*Révision*	Status/*Statut*	Date/*Date*
Creation	1	0	Draft	October 2006
Comments from ESA – Pierre Rebeyre	1	1	Draft	March 2007

Distribution List

Name/*Nom*	Company/*Société*	Quantity/*Quantité*
Bérangère Farges	LGCB	
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TABLE OF CONTENT

1. Introduction

The objective of the study is the analysis of the control loops of the Engineering Waste Compartment (EWC).
Functional Analysis and modelling have been developed in the TN 83.6.
The current Technical Note objective is the description of the foreseen tests and the results of the application of these tests on the process.

The General Conclusion will determine the status of the control, the recommendations and follow-ups than can be given. It represents the state of the art, the image of the process EWC and its controllers at a given moment.
This moment is the end of the tests: 4th October 2006.

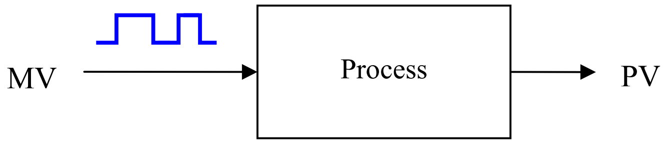
2. Introduction – Test Plan

The objective of the study is to analyse the level 0 control behaviour for the waste compartment. For this, it is necessary to apply tests during normal functioning of the pilot.
According to the first description of the loops to be studied (See Minutes of Meeting 03 November 2005), a preliminary plan test is proposed for the 6 selected loops. The selected loops (with their requirements) are:

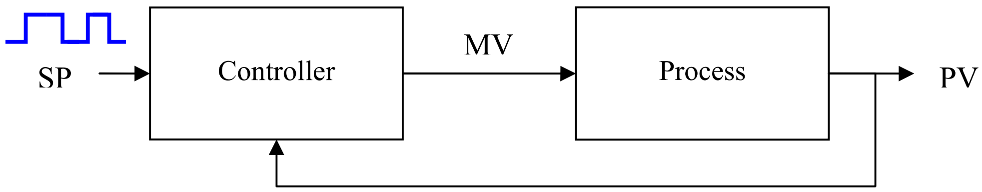
Loop	Pilot requirement	Control specification
Temperature in the bioreactor	see §2.1 in TN83.6	see §2.2.4.1 in TN83.6
Temperature in influent and effluent tanks	see §6.1 in TN83.6	see §6.2.4.1 in TN83.6
Liquid volume in the bioreactor	see §4.1 in TN83.6	see §4.2.4.1 in TN83.6
pH in the bioreactor	see §3.1 in TN83.6	see §3.2.4.1 in TN83.6
Pressure in the gas phase of the bioreactor	see §5.1 in TN83.6	see §5.2.4.1 in TN83.6
Flow rate in the gas analysers	Constant flow for the gas which are analysed continuously	Minimum flow rate = 1 L/min Manual control by means of valves

Two possible ways of tests are possible:

- Open loop test if no control is implemented
  In this case the test signal is applied on manipulated variables of the process



- Closed loop test for the existing controllers.
  In this case the test signal is applied on the set point(s) of the controller.

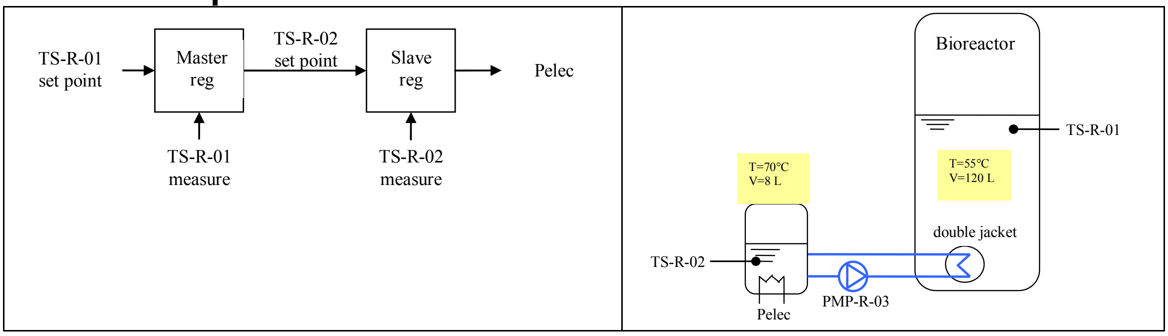


In the Test Plan, the magnitude of the variations of manipulated variables or set points and their durations are only rough estimations. Those values will be adjusted when applying the tests to the EWC:

- the applied magnitude is tuned in order to minimize the disturbance on the reactor, but should be big enough to see a clear result (sufficient ratio signal/noise);
- the duration is tuned in order to have the reactor in a new steady-state condition.

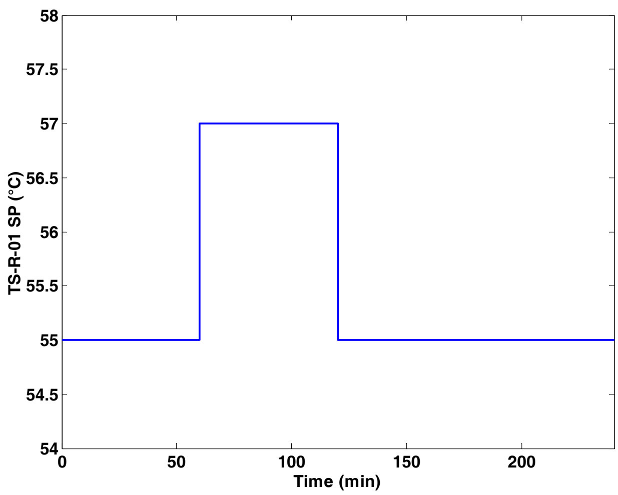
Last descriptions of the control loops are in the chapter 3.

2.1. Temperature control in the bioreactor



Protocol Test: Step change of the set point

- Conditions of tests:
  - No influent injected into the bio reactor.
  - Nominal conditions for the reactor (pressure, volume and pH) and for the hot water tank.



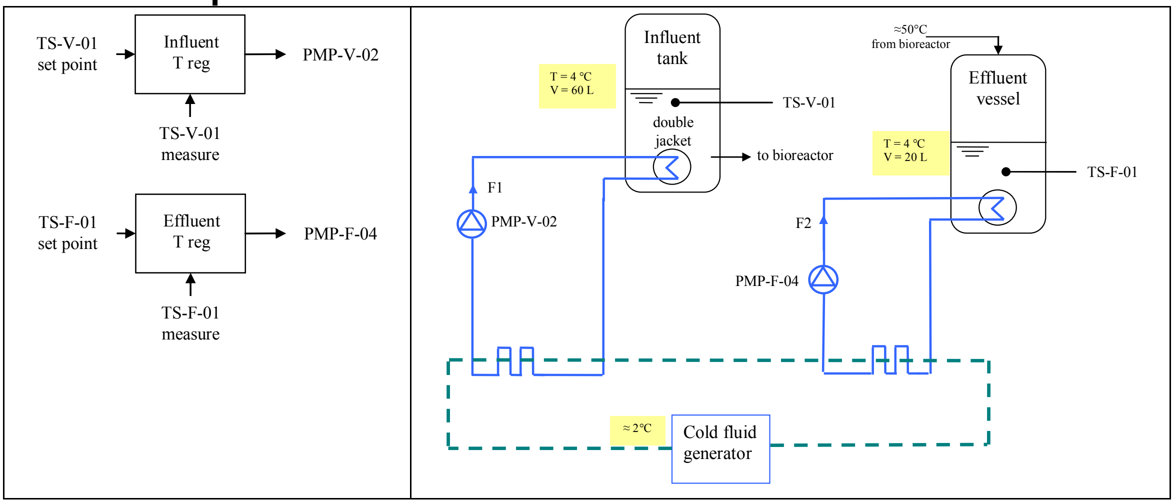
Estimated Duration : 4 hours

The downward step (last two hours) will show the influence of the thermal losses.

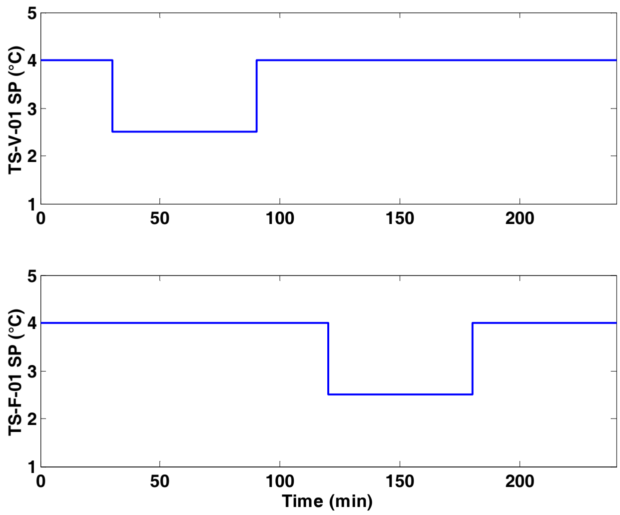
Variables to be recorded:

- TS-R-01 set point and measurement
- TS-R-02 set point and measurement
- Pelec: Electrical power of the heating source.
- V-V-03 valve position (influent input)
- PMP-F-02 pump speed (effluent).
- V-F-08 valve position (effluent side)

2.2. Temperature in the influent and effluent tanks



Protocol Test: Step change of the set points
- Conditions of tests:
  - No influent injected into the bio reactor.
  - Nominal conditions for the tanks.

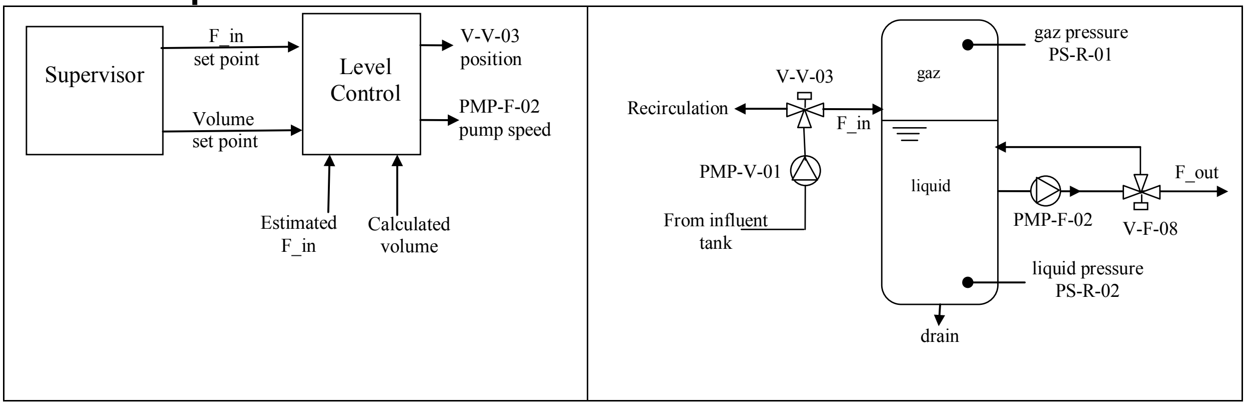


Estimated Duration : 4 hours

The upward steps (last two hours) will show the influence of the thermal losses.

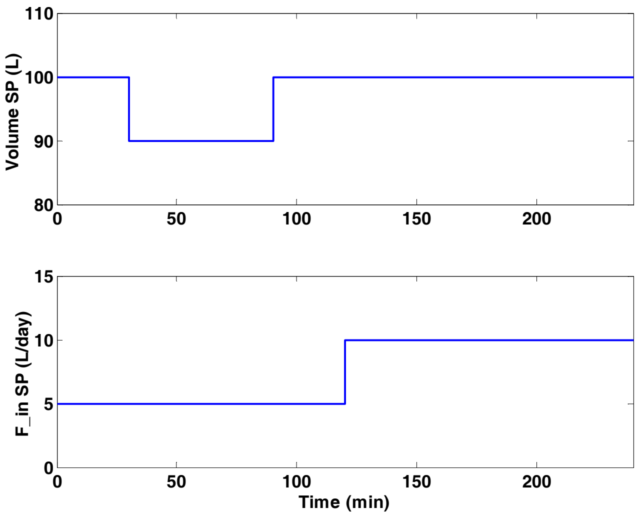
Variables to be recorded:
- TS-V-01 set point and measurement
- TS-F-01 set point and measurement
- PMP-V-02 pump state (on/off).
- PMP-F-04 pump state (on/off).
- Cooling fluid temperature if it exists.
- V-V-03 valve position (influent input)
- PMP-F-02 pump speed (effluent).
- V-F-08 valve position (effluent side)

2.3. Liquid level in the bioreactor



Protocol Test: Step change of the set points

- Conditions of tests:
    - Nominal conditions for the reactor (pressure, temperature and pH).

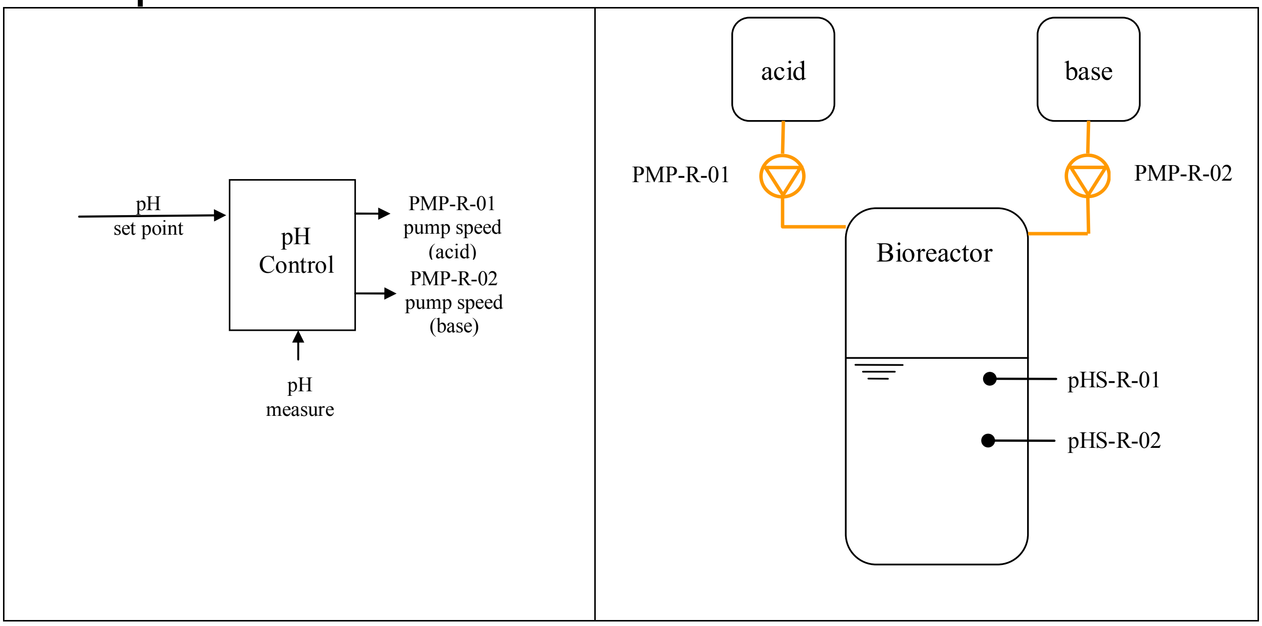


Estimated Duration : 4 hours

Variables to be recorded:

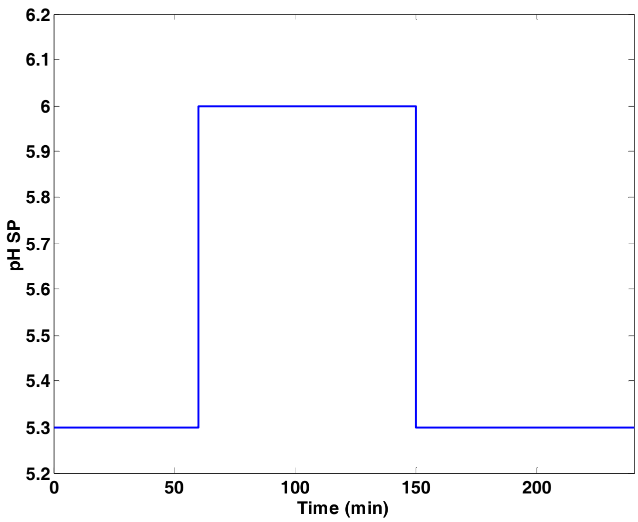
- PS-R-01 gas pressure measurement
- PS-R-02 liquid pressure measurement
- Calculated Level and Volume of the bioreactor
- V-V-03 valve position (influent input)
- Calculated or measured influent flow rate F_in
- PMP-F-02 pump speed (effluent).
- V-F-08 valve position (effluent side)
- Calculated or measured effluent flow rate F_out

2.4. pH in the bioreactor



Protocol Test: Step change of the set point

- Conditions of tests:
    - No influent injected into the bio reactor.
    - Nominal conditions for the reactor (pressure, temperature and volume).

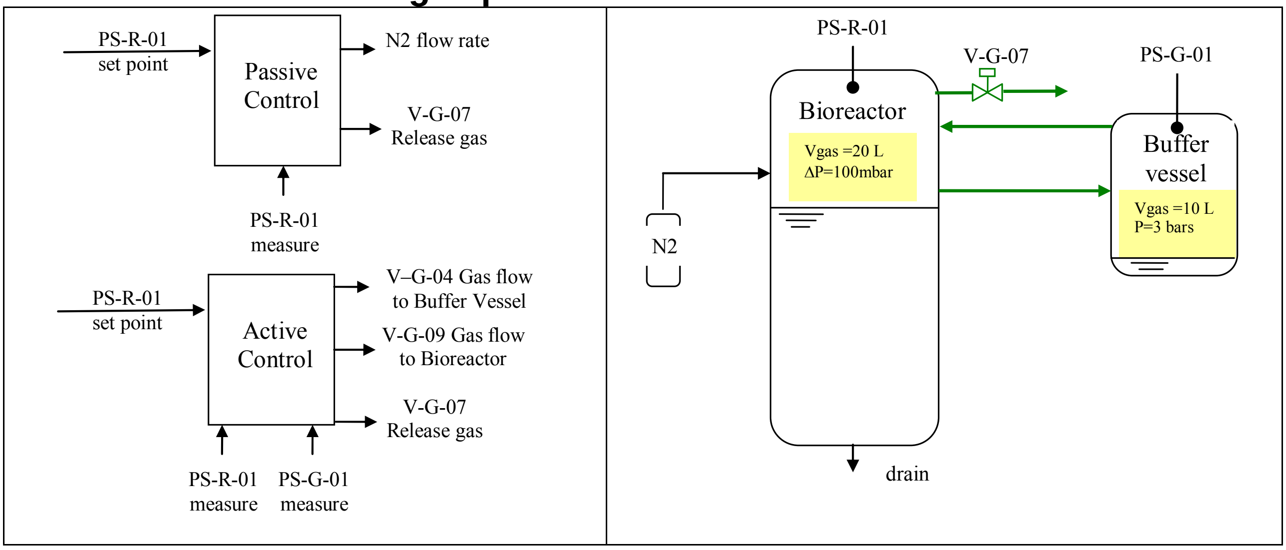


Estimated
Duration : 4 hours

Variables to be recorded:

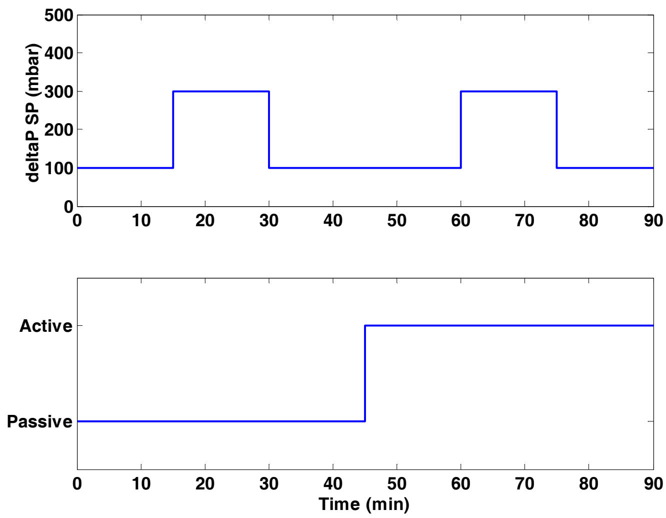
- pHS-R-01 and pHS-R-02 pH measurement
- PMP-R-01 pump speed (acid) and PMP-R-02 pump speed (base)
- V-V-03 valve position (influent input).

2.5. Pressure in the gas phase of the bioreactor



Protocol Test: Step change of the set point

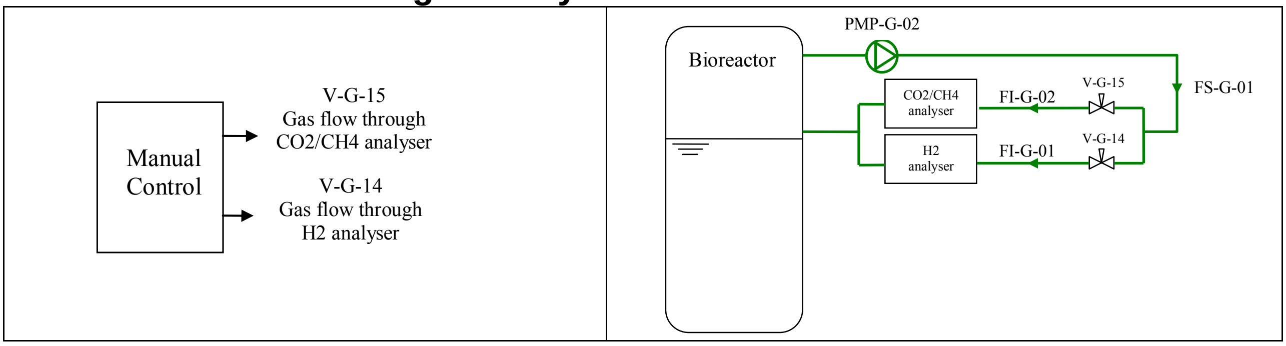
- Conditions of tests:
  - Nominal conditions for the reactor (temperature, volume and pH).



Estimated Duration : 1.5 hours

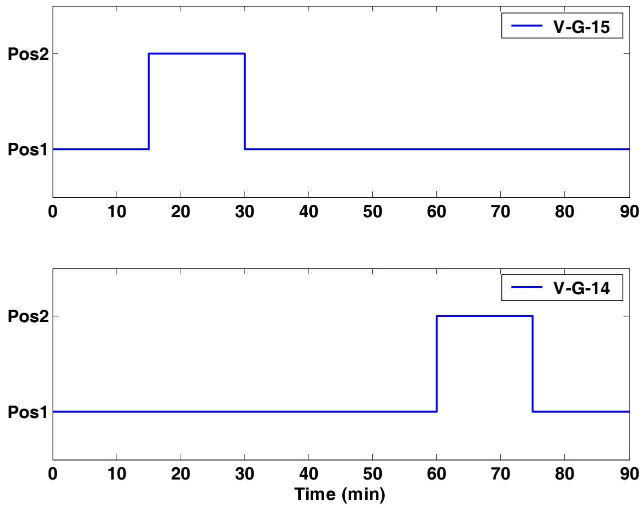
Variables to be recorded:
- PS-R-01 and PS-G-01 pressure measurement
- V-G-04, V-G-07 and V-G-09 valves position
- N2 flow rate into the bioreactor

2.6. Flow rate in the gas analysers



Protocol Test: Step change of manipulated valves.

- Conditions of tests:
  - Nominal conditions for the reactor (temperature, volume, pressure and pH).
  - The two modes of gas pressure control should be considered (passive and active).



Estimated Duration : 1.5 hours

Variables to be recorded:
- FS-G-01, FI-G-01 and FI-G-02 flow rate measurement
- V-G-14 and V-G-15 valves position
- PMP-G-02 speed

2.7. Conclusion

The duration of the preliminary tests for the control expertise is evaluated to: 3 days.

From these tests and their analysis, some complementary tests will be proposed.

Estimated complementary tests duration: 2 days.

3. Tests Report and Analysis

These tests have been performed from 2nd October 2006 to 4th October 2006 in EPAS laboratory.

The test report is presented in relation with the test plan. Please refer to the 2.x chapter, definition of the test, for the presentation of the results in 3.x chapter.

For some tests, the initial test plan could not be applied. Either because the strategy of control has been modified or the process was unavailable for this test.
The control loops affected by modifications with regard to the plan tests are:

- Liquid volume: there is no supervisor. The volume is merely regulated by feeding the reactor at regular scheduled times.
- Gas pressure in passive mode: two thresholds are used instead of a set point.

General conditions of the tests.
During the tests, the bioreactor was in
Nominal conditions:

- Temperature ≈ 55°C
- pH ≈ 5.1
- Volume ≈ 100 L
- Gas pressure ≈ 80 mbar

Except for:

- Influent tank temperature ≈ 15 °C (instead of 4°C)
- No filtrate (the filtration unit was not running, because of clogged membranes)
- Many stops and restarts of the recirculation flow (the main effect of these events is an important disturbance on the reactor temperature).
- No gas analysers (in maintenance)

List of the recorded variables

Table 1 : List of the recorded variables

Tag Name	Description	Unit
SCI_R_T_R_01_SP	Set point Reactor Temperature	°C
TS_R_01_AV	Reactor Temperature for the controller	°C
PID1_Y	Output controller : Heating Water Set Point	°C
TS_R_02_AV	Heating Water Temperature	°C
PID2_Y	Heater Steering	0-100 %
SCI_R_PH_R_01_SP	pH Set Point	
PH_R_01	pH Measurement 1	
PH_R_02	pH Measurement 2	
R_PH_PID1_Y	Output of the pH controller (Split Range)	-100-100%
PMP_R_01	Acid pump	0/1
PMP_R_02	Base pump	0/1
V_V_03	Feed Valve position	0/1
SCI_V_FEED_VOLUME_SP	Reactor Volume Set Point	L
R_R_01_volume	Reactor Volume	L
SCI_V_FEED	Feed Control	0/1
PMP_F_02	FU pump state	0/1
PMP_F_02_SPEED	FU pump speed	%
V_F_08	To Effluent vessel valve position	0/1
FS_F_01	Recirculation from FU flow Rate	L/mn
SCI_V_T_V_01_SP	Influent Temperature Set Point	°C
TS_V_01_AV	Influent temperature	°C
HX_V_001	Cooler Steering	0/1
PS_R_01	Reactor gas pressure	mbar
PS_G_01	Buffer Vessel gas Pressure	mbar
PMP_G_01	Pump state from reactor to buffer vessel	0/1
V_G_09_SP	Set point for valve from buffer vessel to reactor	%
V_G_29_SP	Set point for valve from N2 to reactor	%
PS_G_04	Gas pressure in exhaust buffer	mbar
V_G_07	Inlet valve for exhaust tank	0/1
V_G_08	Outlet gas for exhaust tank	0/1

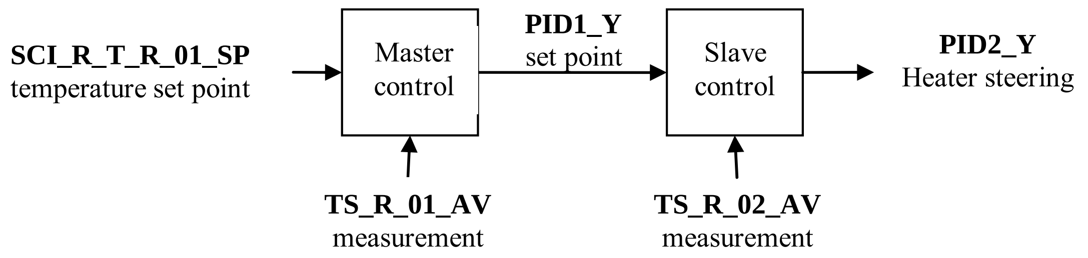
Remark: 0/1 can also be represented by off/on

These variables have been recorded in iFix system.
Variables beginning **SCI**_* are variables for **SC**ada **I**nterface. Changeable by the user.

Acquisition period is 10 seconds for the most part of the tests. For long tests (pH) the acquisition period can be 1 minute.

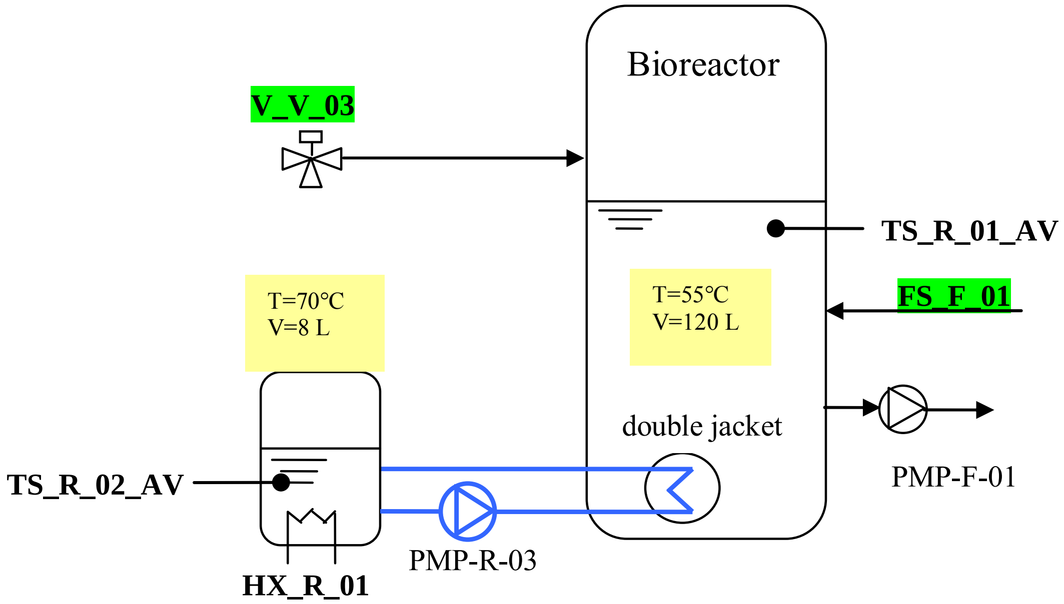
3.1. Temperature control in the bioreactor

Remind of the control strategy:



Master PID controller
Slave PID controller

PID2_Y is the input of a PWM. Heater power is HX_R_01



Disturbances for the control are :

- Feed represented by the Valve opening **V_V_03**
- Recirculation ON or OFF represented by **FS_F_01** measurement of the recirculation flow rate (sludge return flow from the filtration unit).

3.1.1.Response to set point change

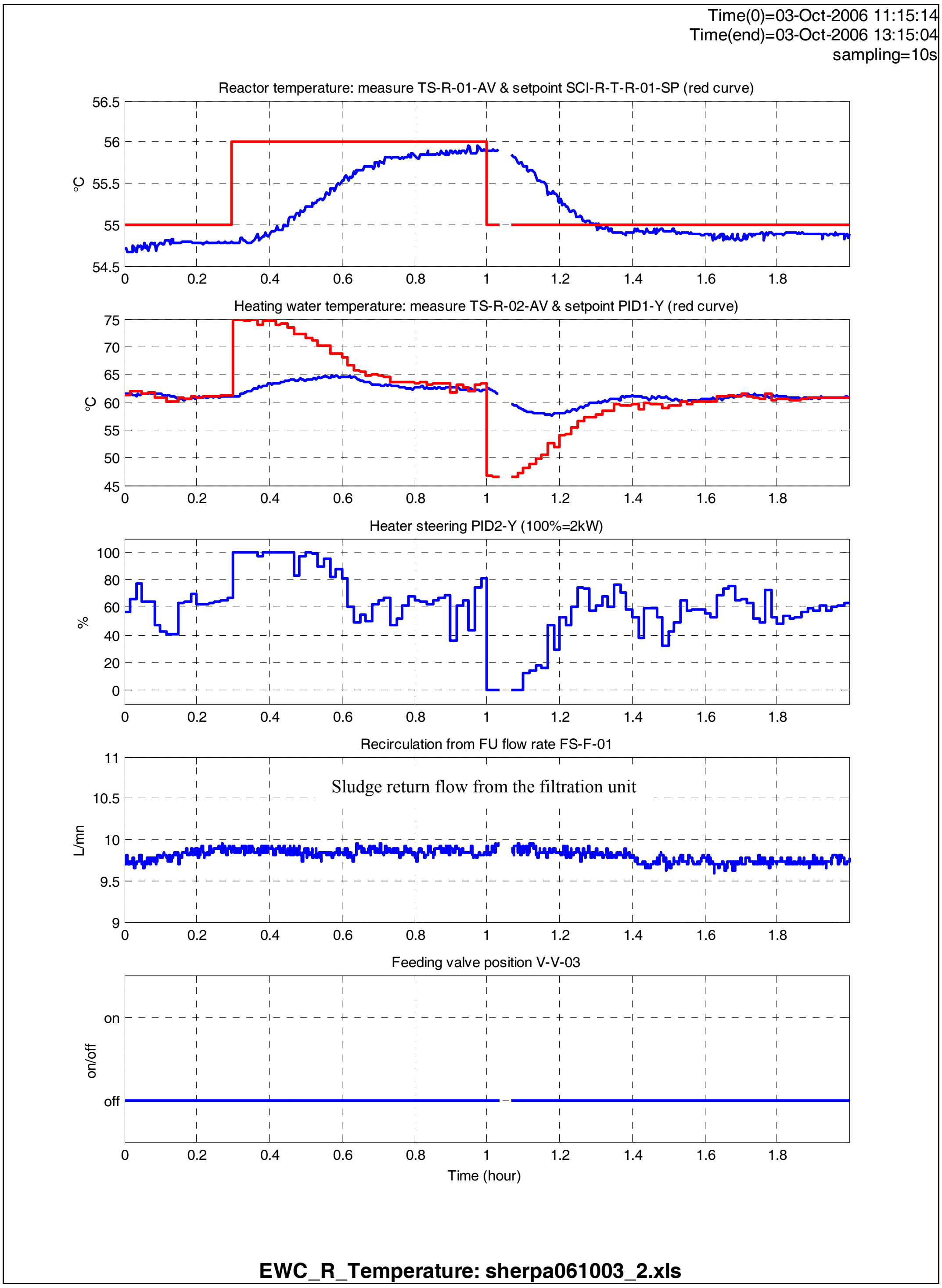


Figure 1: response of the reactor temperature to set point change

Set points were changed from 55°C to 56°C and from 56°C to 55°C.
The process was in nominal conditions during the test.

Response Time:

- About 30 to 40 minutes for the positive change
- About 20 minutes for the negative change

The different of behaviour can be explained by the thermal losses (for the negative change) and by the saturation of the action, positive and negative but not the same time.

→ **Set point is satisfied**. +/- 0.2 °C from the set point in steady state condition. Behaviour of the action (heating) is satisfactory.

3.1.2.Response to disturbances

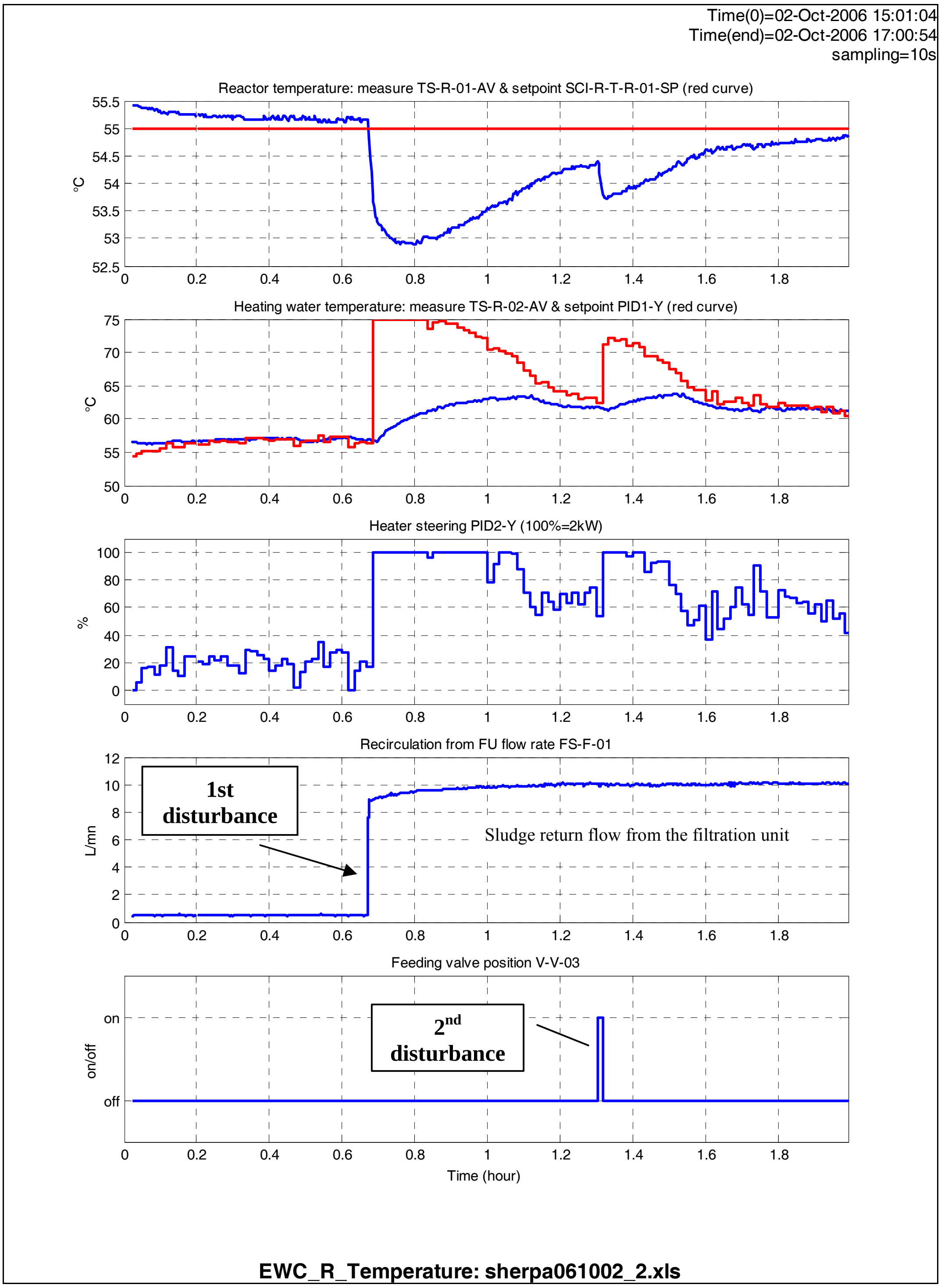


Figure 2: response of the reactor temperature to disturbances

1st disturbance: restart of the recirculation flow
The recirculation pipes are not completely isolated. There are thermal losses in the recirculation part and also a difference of temperature (depending mainly on the time of inactivity of the recirculation unit) In consequence the reactor temperature decrease ≈ **-2°C**
Remark: the action (heating) is saturated and it is not possible to be better. Excepted if the heater is more efficient.
→ The control behaviour is the best which can be done for a PID control.

2nd disturbance: feeding of influent product (Feed temperature is about ≈13°C in this test)
→ reactor temperature decrease ≈ **-0.5°C**
This decrease will depend on the feed duration.

3.1.3.Reactor temperature in nominal conditions

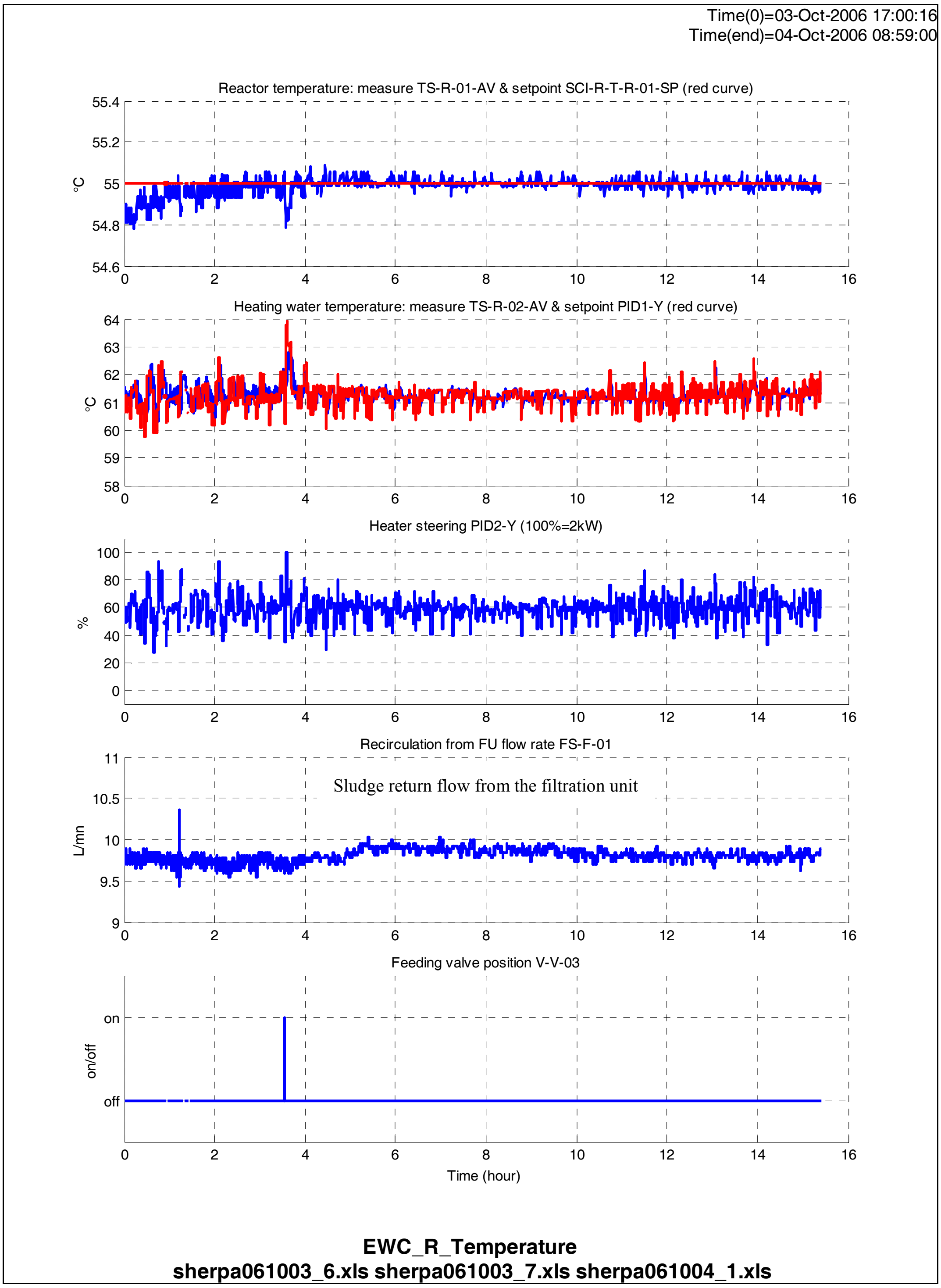


Figure 3: reactor temperature in nominal conditions (i.e. with steady state recirculation)

The behaviour of the temperature control in nominal conditions is satisfactory.

In this recording (about 16 hours):
- Temperature is controlled +/- 0.05 °C
- A normal feeding of the reactor implies a disturbance of 0.2 °C

→ **Reactor Temperature satisfies the requirements**

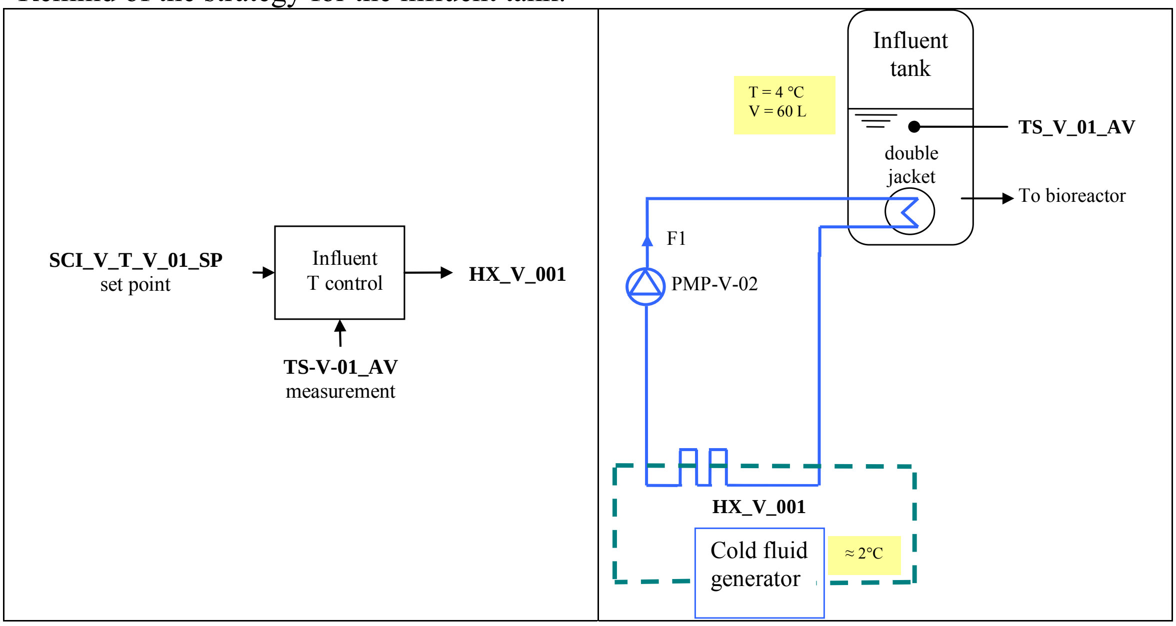
3.2. Temperature in the influent and effluent tanks

No test was performed for this control. The cooler is not efficient enough to satisfy the set point.

Temperature if the influent tank is 12 °C and the cooler HX-V-001 is always ON.

→ It is not possible to satisfy the objective.
→ The cooler should be changed
During the period of tests (2nd October to 4th October), an attempt for using a second cooler was done, without the expected result.

Remind of the strategy for the influent tank:



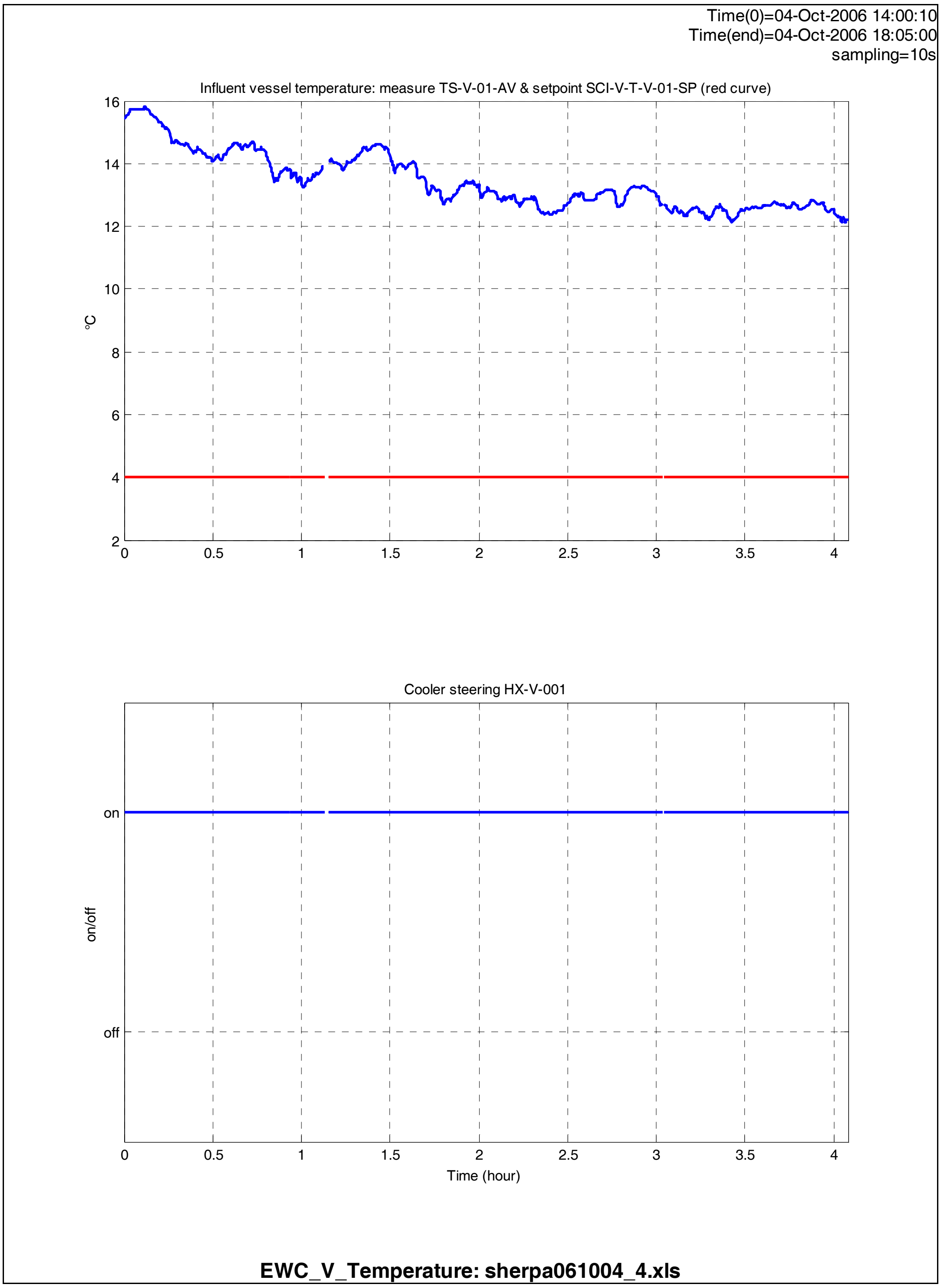
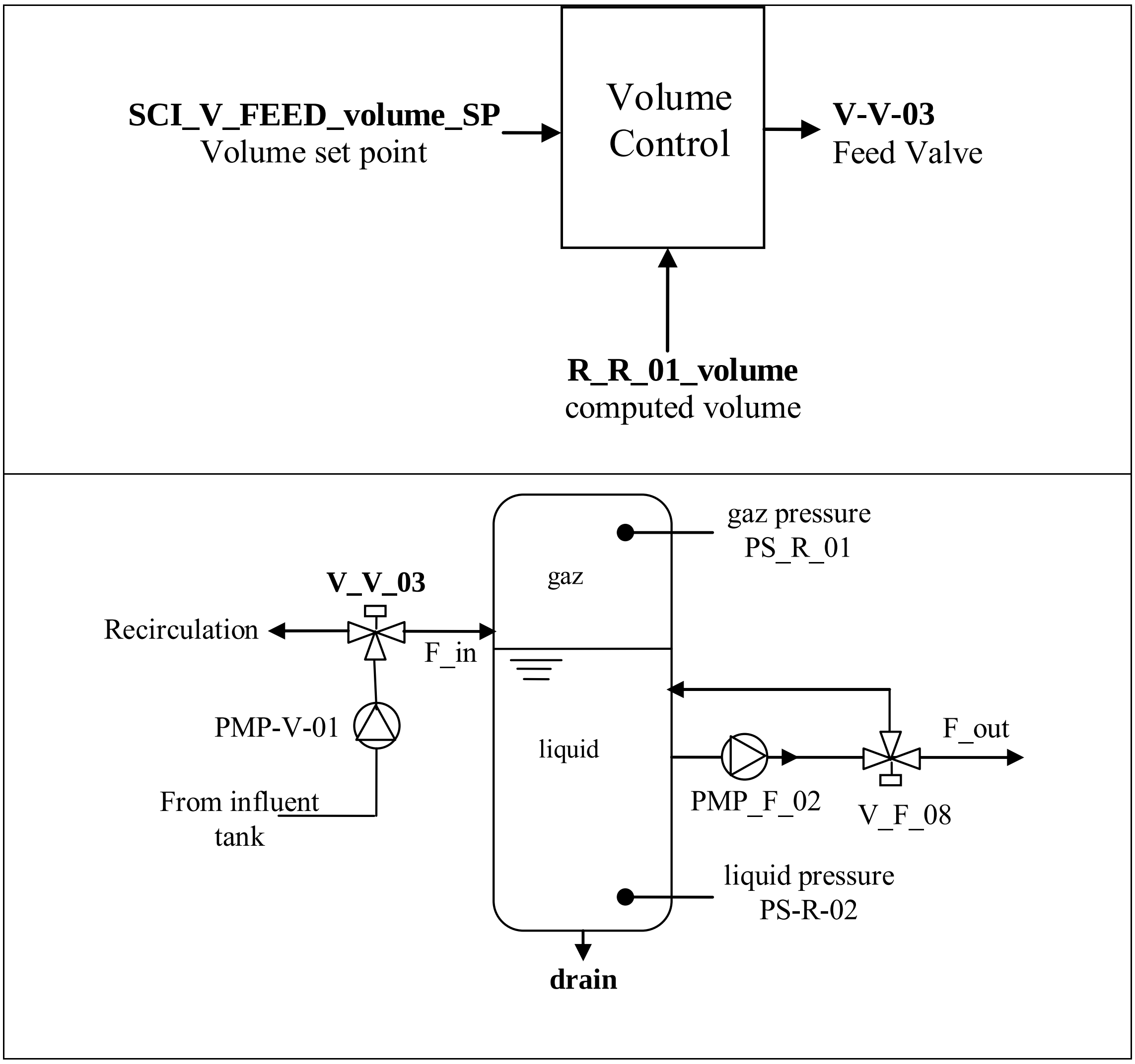


Figure 4: temperature in the influent tank

3.3. Liquid level in the bioreactor

The volume is controlled by feeding at regular scheduled times (every 1 hour for instance).
The filtration unit was not running, so only the response to a draining disturbance (drain≈5L) was analysed. (see Figure 5)
Figure 6 displays the normal behaviour of the control.

Remind of the current control strategy:



At regular scheduled time, the feed valve is open until the volume is greater than the set point.
Remark: because of the data acquisition sampling period, the measurement of volume above 100 l does not appear. Nevertheless feeding was stopped when volume R_R_01_volume was greater than the set point 100 litres.

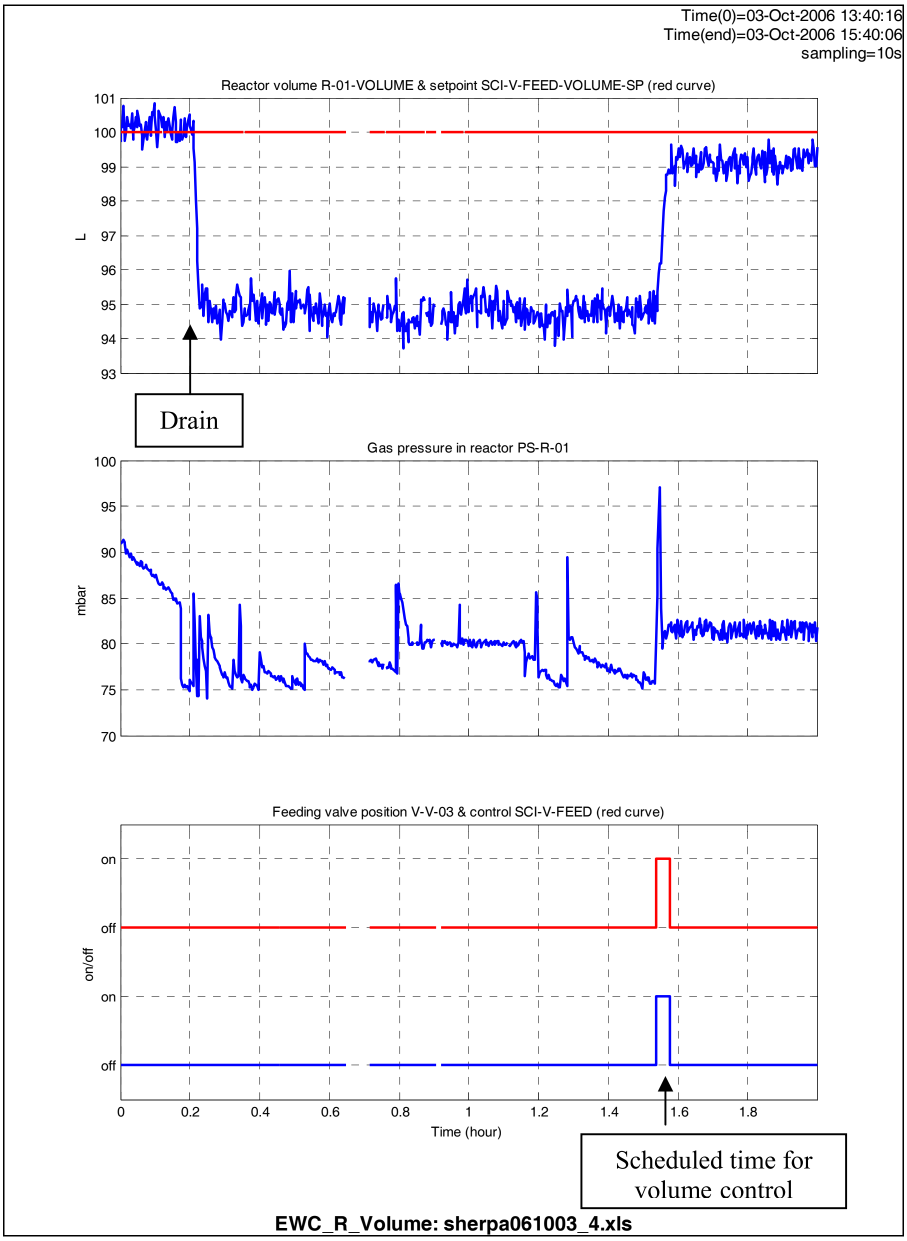


Figure 5: response of reactor volume control to a drain disturbance

Normal behaviour of Volume:

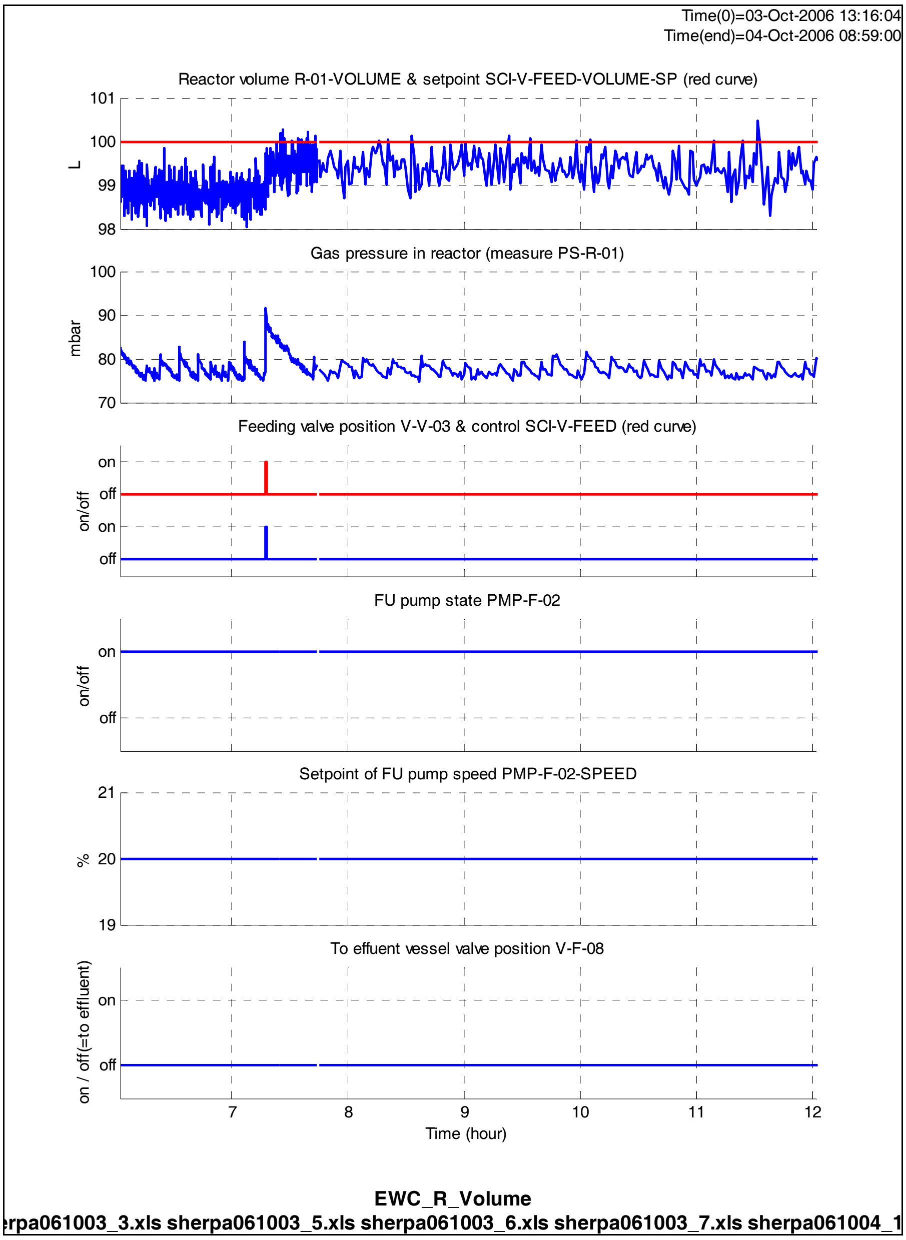
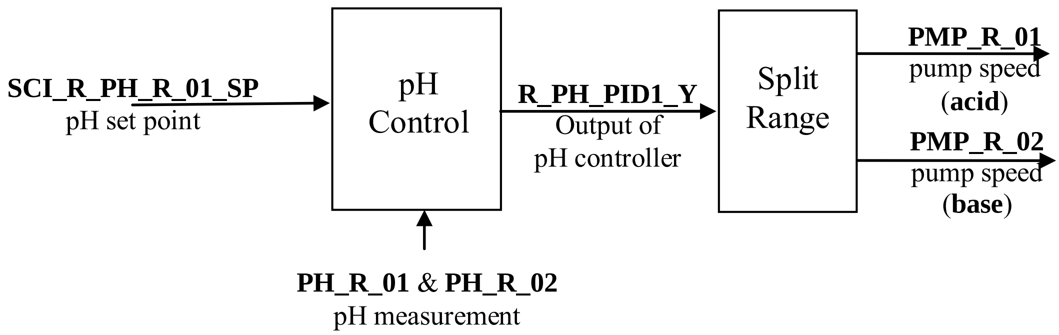


Figure 6 : normal behaviour of the volume control

Conclusion: Volume control satisfies the requirements.

3.4. pH in the bioreactor

Remind of the Control strategy



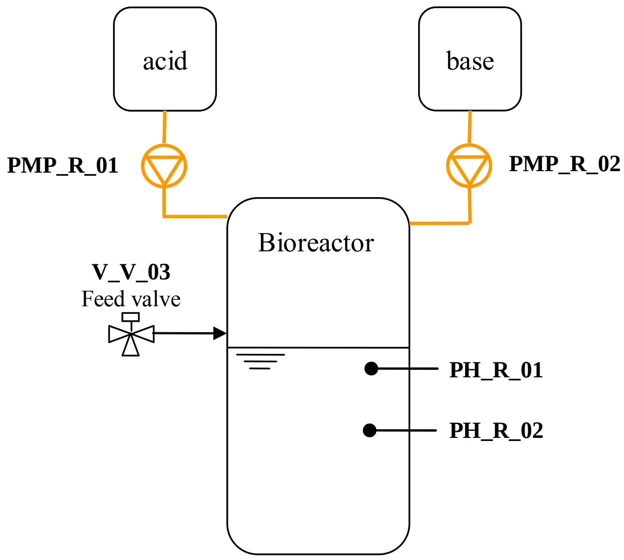
pH control is completed with a **Split-Range**.
Output of the control **R_PH_PID1_Y**. Range is -100/+100

-100/0 : **acid** action

0/100 : **base** action

pH control includes a **Dead Zone**

+/- 0.03 during the tests



Two measurements for the pH : PH_R_01 and PH_R_02
Two actions : acid PMP_R_01 and bas PMP_R_02
Disturbance : feed, represented by the feed valve V_V_03.

3.4.1. Response to set point change

After the set point change, the integrative part of the PI should decrease to 0, before becoming negative. When negative, Acid pump is active, through a PWM (Pulse Width Modulation) to decrease the pH.

When pH measurement (PH_R_01 (blue) is used here) enters into the dead zone (+/-0.03), action is stopped.

The response time, after the integrative deflation part, is about 3 hours.

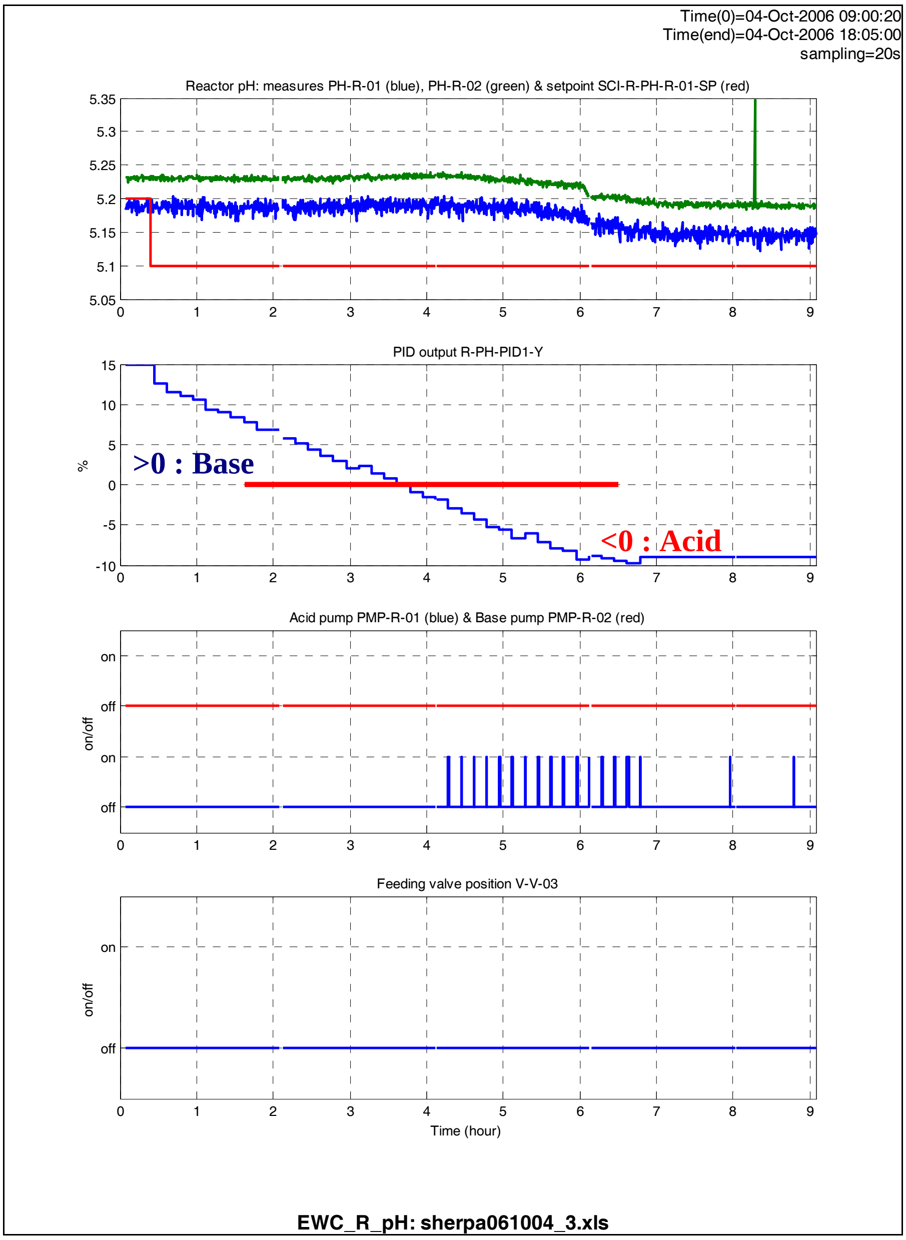


Figure 7: response of pH reactor to a set point change

3.4.2. Response to disturbances

The disturbance is the feeding of influent product (which is acid in this test). The reactor pH decrease ≈ -0.1

The time necessary for the pH to come back to the set point (in the dead zone around the set point) is about 3.5 hours

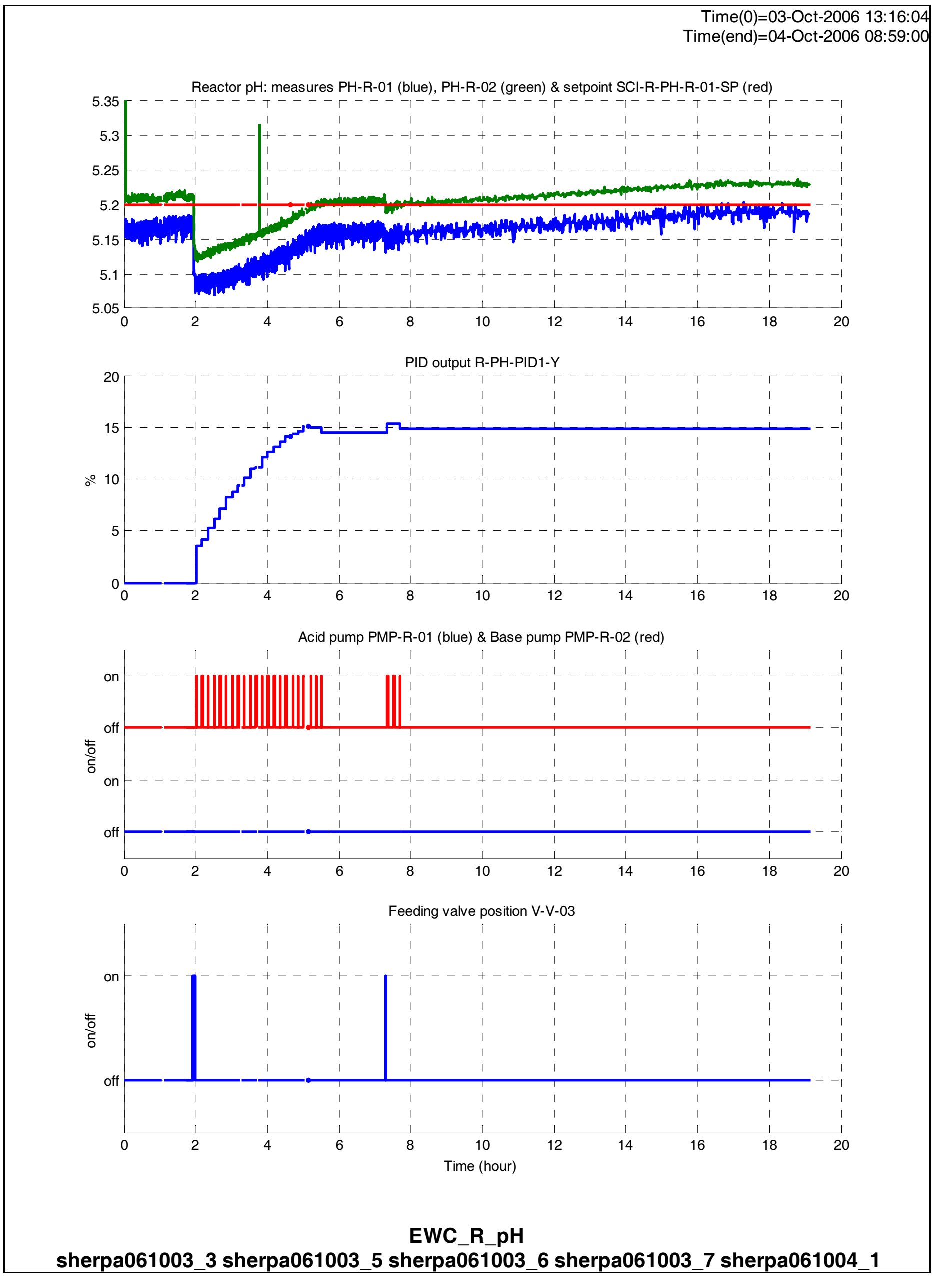


Figure 8: response of pH reactor to disturbances

Conclusion for pH control

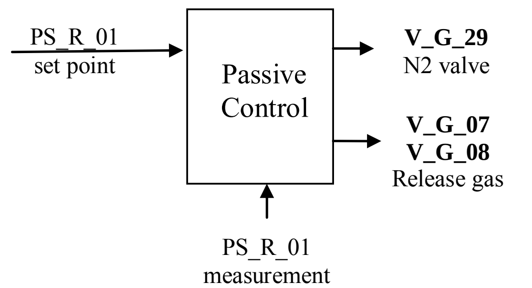
The pH control is running correctly and the requirements are satisfied.

3.5. Pressure in the gas phase of the bioreactor

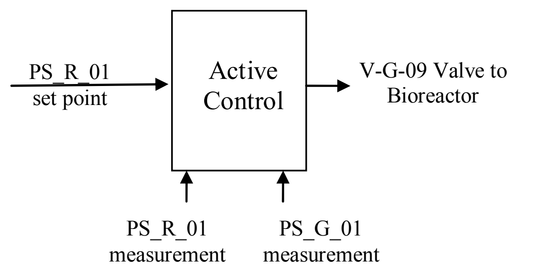
Tests on both modes were performed:

- In passive mode (PMP-G-01 off), change of thresholds for N2 flush
- In active mode (PMP-G-01 on), change of gas pressure set point

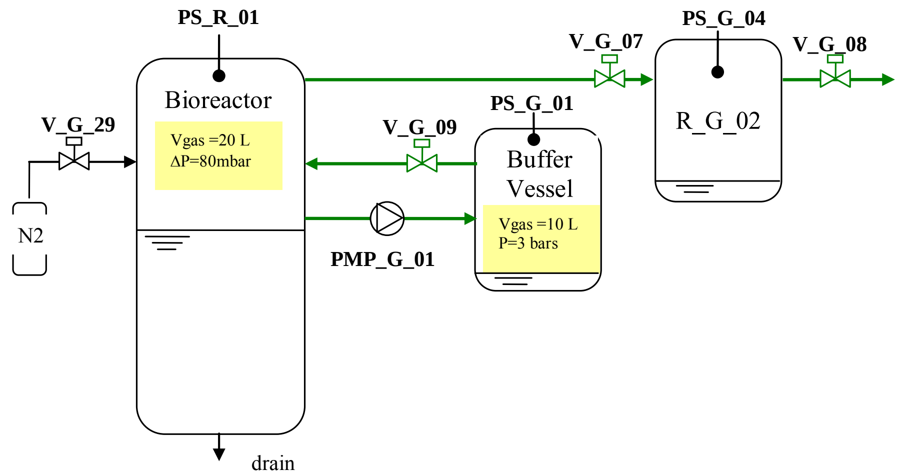
Remind of the current control strategy



- If pressure is lower than a threshold (ie 75 mbars), injection of N2 → V_G_29 opening
- if pressure is greater than a threshold (ie 90 mbars), release gas to R-G-02 and out.



- Pressure PS_R_01 is controlled with the valve V_G_09 from Vessel to Bioreactor if pressure PS_G_01 is lower than 3 bars.
- If pressure PS_G_01 exceeds 3 bars, this pressure is controlled to 3 bars with the valve V_G_09.



3.5.1.Active Strategy

See Figure 9. Because of the data acquisition sampling period, all the phenomena are not visible on the graph.

For this test the pressure into the Buffer Vessel R-G-01 was about 2.5 bars. In this condition, it is possible to control in active mode the pressure in the reactor, by the action on the valve V_G_09.

In case of overpressure in the reactor (here the threshold is equal to 90 mbars), the correspondent passive action works.
In the figure, action **A** corresponds to a pressure above 90 mbars, even if it does not appear in the plotting because of the acquisition sampling period.

In normal conditions, the control of pressure is correct. A set point change is correctly followed and the deviation between the set point and the measurement is about +/2 2 mbars.

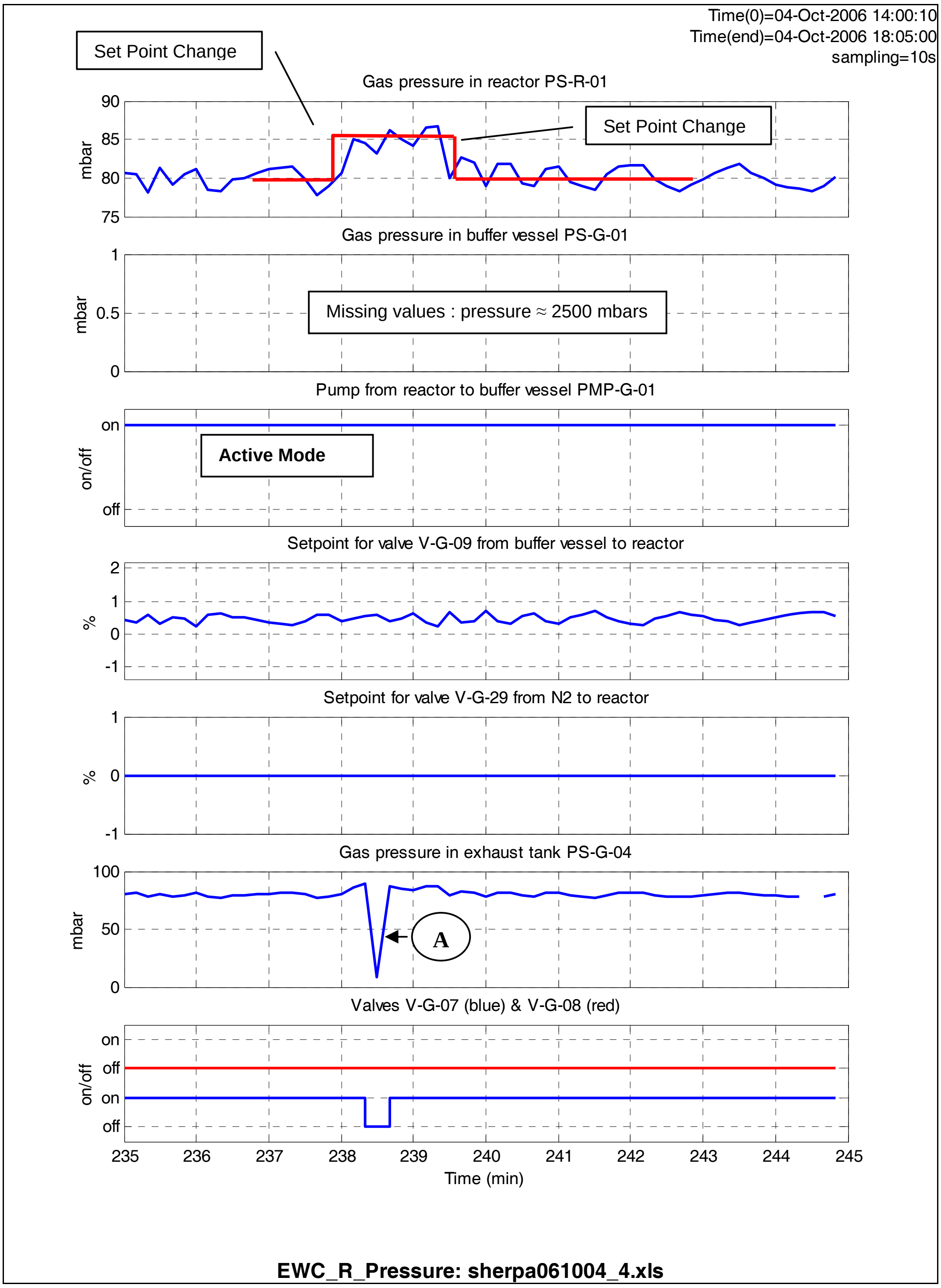


Figure 9 : Active Strategy control of pressure

3.5.2.Passive Strategy

The passive strategy is not a strict control strategy but is used to prevent the reactor pressure to be:
- Below 75 mbars
- Above 90 mbars.

The Figure 10 demonstrates the first requirement (limit at 75 mbars)
A manual leak was caused to decrease the pressure till 77 mbars.
A natural leak decreases the pressure. When below 75, N2 is automatically introduced in the reactor.

→ Behaviour correct

The Figure 11 demonstrates the second requirement (limit at 90 mbars)
When the pressure is above 90 mbars (intentionally here), the procedure of release gas with the valves V_G_07 and V_G_08 is working until the pressure comes back below the limit.

→ Behaviour correct

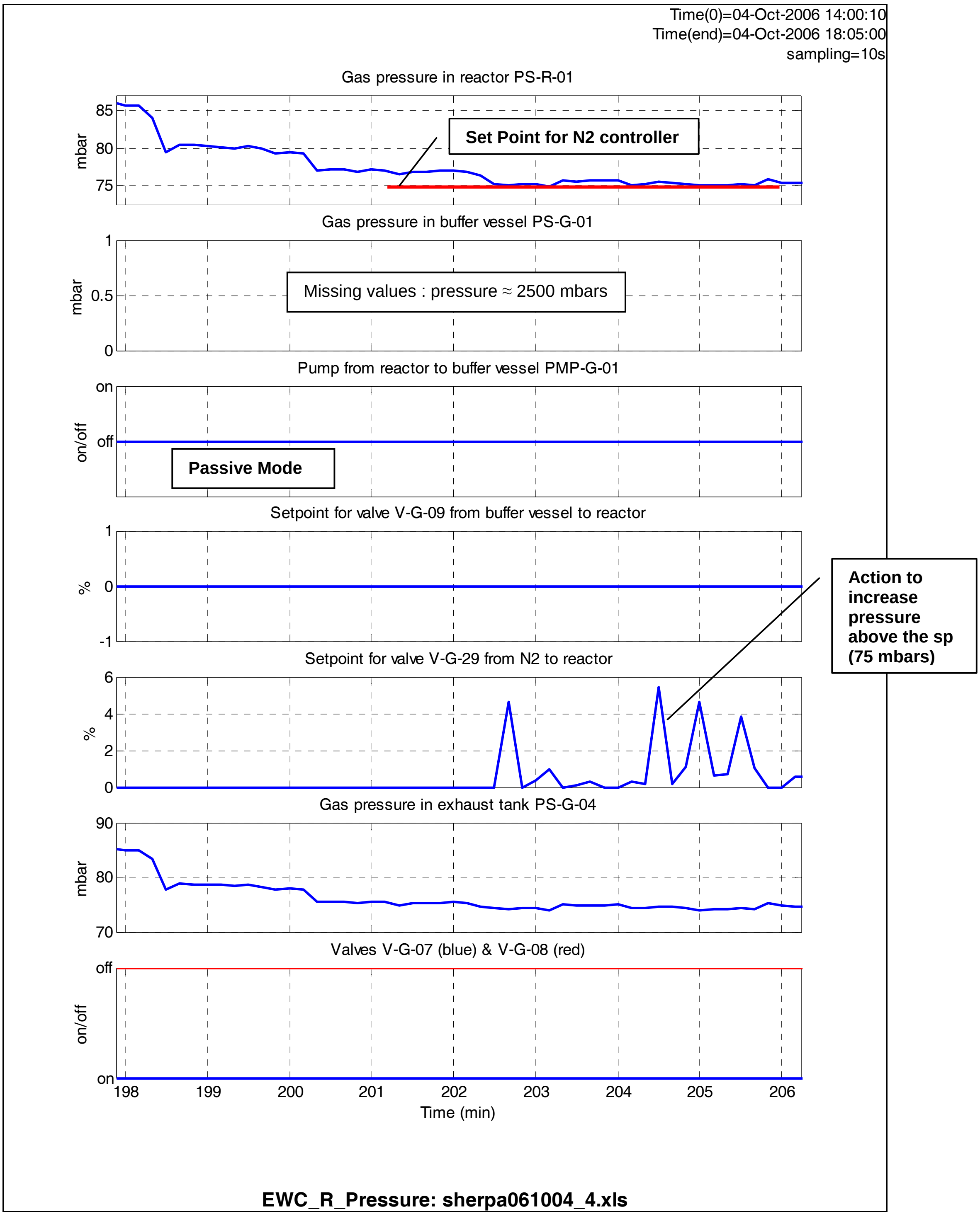


Figure 10 : Passive Strategy control of Pressure (Part 1)

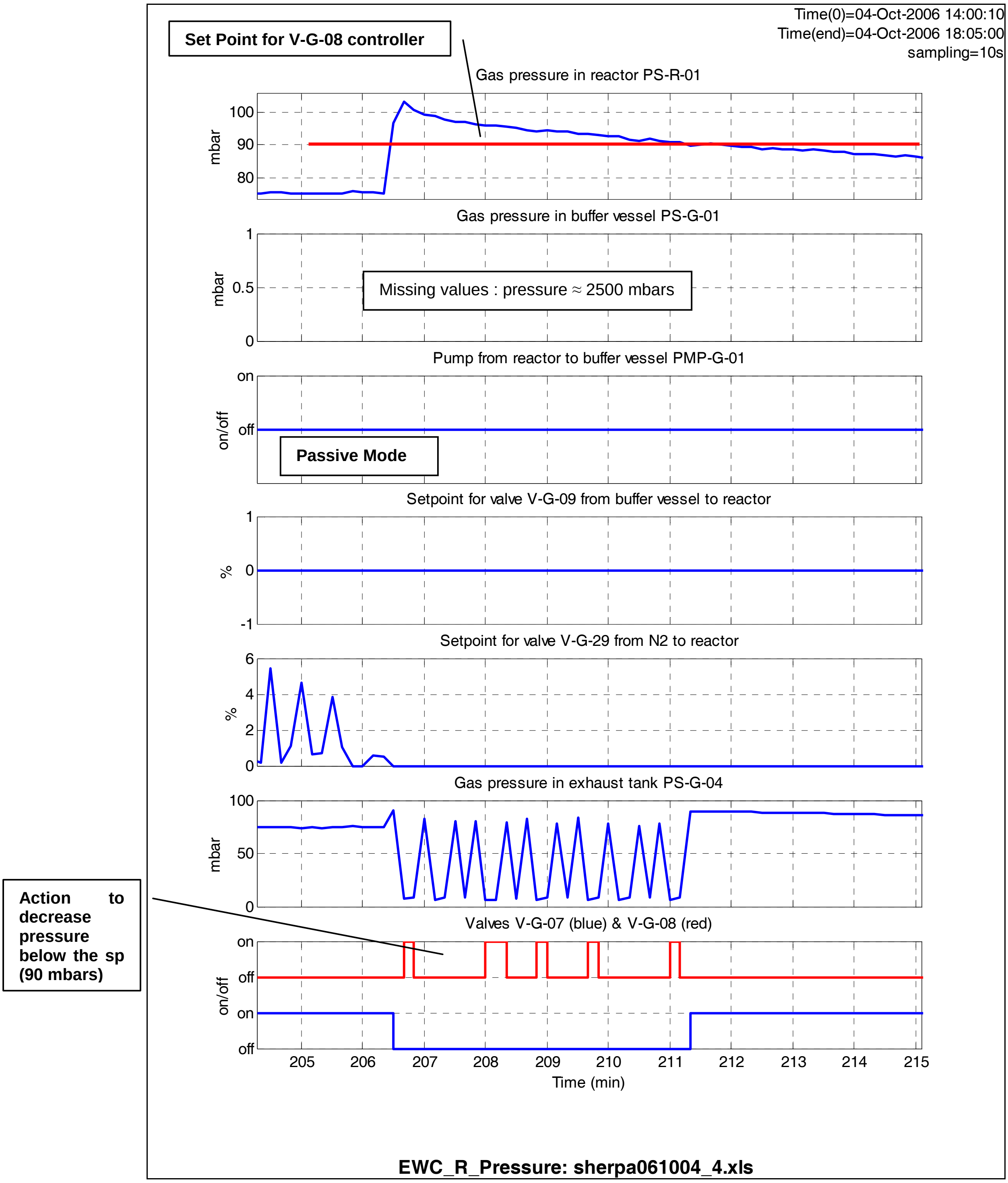


Figure 11 : Passive Strategy control of Pressure (Part 2)

3.6. Flow rate in the gas analysers

No tests. The gas analysers were not available during tests campaign.

4. General Conclusion

Loops	Control behaviour	Remarks
Temperature control in the bioreactor	OK	
Temperature in the influent and effluent tank	no results	Process not available. To be done.
Liquid volume in the reactor	OK	
pH in the bioreactor	OK	
Pressure in the gas phase	OK passive mode OK active mode	
Flow rate in the gas analysers	no results	TBD when gas analysers available

After the retuning and the modifications of some strategies during the study and the tests, it can be said that the current control loops are running correctly for the process and that the requirements are satisfied.

Some loops could not be tested during the tests because of the non availability of some physical parts of the process. Nevertheless, these missing loops should not be a problem.

5. Appendix: Document evolutions

5.1. Issue 1 / Revision 1

Page/Section	Comment	Answer
General	The test procedures/results show deviations with the test plan (the planned ramps (pH, T, etc.) have apparently not been tested). Could you please explain the differences? (see table 2 below for details)	In the test plan, the magnitude of the variations and their durations were only rough estimations, made several months before performing the tests. Those values have been adjusted during the tests, after discussion with EPAS, and several trials. * the applied magnitude is tuned in order to minimize the disturbance on the reactor, but should be big enough to see a clear result (sufficient ratio signal/noise) * the duration is tuned in order to have the reactor in a new steady-state condition. A comment in p 5 section 2 is added. See table 2 below for additional answers.
General	Could you please repeat the requirements to be verified together with the test plan or refer to adequate TN?	A table in section 2 gives references to the requirements defined in TN83.6.
p 8, Section 2.3	We assume the operating conditions of the bioreactor were nominal. Could you please clarify? Could you please also precise which gas loop was functioning (active or passive, as well as pressure set point)?	1) Nominal operating conditions for temperature, pressure and pH. 2) During all the temperature, liquid volume & pH tests, the gas pressure was in passive mode, with the 2 following thresholds: * flush of N2 into the reactor if pressure is too low (75 mbar) * release of gas outside the reactor if pressure is too high (>90 mbar)
p 9, Section 2.4	We assume the operating conditions of the bioreactor were nominal except for pH. Could you please clarify?	Nominal operating conditions for temperature, pressure and volume.
p 10, Section 2.5	We assume the operating conditions of the bioreactor were nominal except for pressure. Could you please clarify?	Nominal operating conditions for temperature, volume and pH.
p 11, Section 2.6	We assume the operating conditions of the bioreactor were nominal. Could you please clarify? Could you please also precise which gas loop is used (passive/active) as pressure set point is not exactly the same for both cases.	1) Nominal operating conditions for temperature, volume, pressure and pH. 2) The tests regarding the flow rates in the gas analyzers were not performed. If done, the two modes of gas pressure control should be considered.

p12, Section 3	Could you please give more details addressing which control loops are affected by changes in the strategy of control?	The control loops affected by modifications with regard to the plan tests are: * liquid volume: there is no supervisor. The volume is merely regulated by feeding the reactor at regular scheduled times. * gas pressure in passive mode: two thresholds are used instead of a set point.
p14, section 3.1	One of the disturbances for the temperature is recirculation. According to graphs shown on pages 15, 17 and 19, this recirculation corresponds to the sludge return flow from the filtration unit. Could you please clarify this point?	Yes, this recirculation corresponds to the sludge return flow from the filtration unit.
p 26, Section 3.4.1	Apparently, the disturbance to pH is far less important and opposite to what is specified in section 2.4. Could you please clarify?	After discussion with EPAS, it was better (for the reactor population) to decrease the pH than to increase it. Similarly, the pH variation was minimized.
p 26, Section 3.4.1	According to the explanation, an integration time is necessary before action is taken on pH. In total, the time to reach the new pH set point is the sum of this integration time and of the active time (being estimated as 3 hours). According to figure 7, no less than 6 hours in total are needed to reach the new setpoint. Does this mean the integration time is 3 hours? Can this integration time be minimised?	Yes, in that case, the integration time is around 3 hours. But this value depends of the initial value of the PI controlled, which results for actions performed in the past in response to disturbances or set point changes. This integration time could be minimised, by adding other blocks in the control. But two comments have to be made: * it is better to wait a certain time before switching from one reagent to the other one. The integration time gives that kind of delay. * the pH variation here is rather slow. In case of a larger PH error, the integration time will be smaller.
p27, section 3.4.2	According to figure 8, a disturbance of similar amplitude as the setpoint modification in section 3.4.1 is performed by feeding influent. In this case, the pH returns to its nominal value within 3.5 hours, which somehow corresponds to the response time mentioned in previous section. Could you please explain the different behaviour of the pH control system for different perturbations which are of similar amplitude (i.e. no time needed for integration in this case)?	In that case, the integration time is 0 because at the beginning of the test the initial value of the PI controller is 0. Remember that this value results from past pH deviations from its set point.

p28, section 3.4.2	The time needed to recover after pH changes seems to be rather long. In case pH disturbance +-0.1pH are caused by compartment feeding, the time currently needed to recover nominal pH may be to long to ensure nominal conditions in the bioreactor (i.e. pH SP = 5.2, Feed every 3 hours causing 0.1pH decrease anytime. Will C1 ever run at pH = 5.2?). Could you please provide us with your opinion on this point?	The variation of pH (-0.1) results of a 5 L feeding of the reactor, following a 5 L draining (see Figure 5 in section 3.3). This is a rather big disturbance. The normal feeding volume is much smaller, so is the pH variation related to feeding. See for instance the 2nd feeding at time 7.5 hour on figure 8 (p 27 section 3.4.2). The pH variation due to this "normal" feeding is less than -0.02. According to the pH requirements defined by EPAS, the pH should remain between 5.1 and 5.4. The current pH control strategy enables to have the pH in this range, for normal feeding disturbance.

Control loop	Planned tests	Remarks	Performed tests	Remarks	SHERPA's answer
Temperature control in bioreactor	Temperature increase 2C		Temperature increase 1C		1 C to minimize process disturbance sufficient for performance evaluations
	Hold new temperature 1 hour		Hold new temperature 1/2 hour		Hold new temperature 3/4 hour, sufficient for getting a new steady state
	Temperature decrease 2C		Temperature decrease 1C		1 C to minimize process disturbance sufficient for performance evaluations
Temperature control influent and effluent		NO HARDWARE AVAILABLE, OK			
Liquid Level in Bioreactor	Change SP (Decrease to 90 L)		Drain 5L	No filtration unit available, OK	Due to the discontinuous volume control strategy, evaluation of the performance regarding a disturbance is equivalent to evaluation regarding a set point change.
	Hold new SP for 2 hours		Feed flow rate: ??		Feeding is discontinuous. The reactor is fed at regular scheduled times. There is no feed set point for the control of the reactor.
	Change SP (Increase to 100 L)			Does this test need to be repeated in order to monitor the effect of reduced volume (as set point) on the filtrate production pump?	No.

	Feed @ 5L/day				Feeding is discontinuous. The reactor is fed at regular scheduled times. There is no feed set point for the control of the reactor.
pH in the bioreactor	pH increase (+ 0.7)		pH decrease (-0.1)		From reactor content safety, it is better to decrease pH, and the variation has to be low.
	hold new pH for 80 min		Hold new pH for 9 hours		9 hours were required to get a new steady state point.
	pH decrease (-0.7)		No pH increase!		No pH increase, due a lack of time. The response to a feeding disturbance shows the behaviour when pH is lower than its set point.
Pressure in the bioreactor (repeated with active gas loop)	SP increase (+200 mbar)		SP increase (+5 mbar)	Hardware limitation	The passive thresholds are 75 and 90 mbars. So to test the active strategy, the set point variations should be small enough not to have the pressure exceed this range.
	Hold new SP for 10 min		Hold new SP for 10 min		
	SP decrease (-200 mbar)		SP decrease (-5 mbar)		
				Due to specific passive gas loop constraints, similar test was not performed but a different one which verifies correct actions are taken when the system reaches its control	

				boundaries, OK	
Flow rate in the gas analysers		NO HARDWARE AVAILABLE, OK			

Table 2