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Report

Upgrade of the Gas Flow Control System of the Resistive Current Leads of the LHC Inner Triplet Magnets: Simulation and Experimental Validation

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Keywords: control, valve, flowmeter

Abstract

The 600 A and 120 A circuits of the inner triplet magnets of the Large Hadron Collider are powered by resistive gas cooled current leads. The current solution for controlling the gas flow of these leads has shown severe operability limitations. In order to allow a more precise and more reliable control of the cooling gas flow, new flowmeters will be installed during the first long shutdown of the LHC. Because of the high level of radiation in the area next to the current leads, the flowmeters will be installed in shielded areas located up to 50 m away from the current leads. The control valves being located next to the current leads, this configuration leads to long piping between the valves and the flowmeters. In order to determine its dynamic behaviour, the proposed system was simulated with a numerical model and validated with experimental measurements performed on a dedicated test bench.

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INTRODUCTION

The 600 A and 120 A circuits of the inner triplet magnets of the Large Hadron Collider are powered by resistive gas cooled current leads [1,2].The gas flow through theses leads is controlled by an indirect temperature measurement which induce severe limitations in the operating parameters of these circuits, in particular during the current variation phases. In addition to these limitations, the temperature sensors used for the regulation are located in a difficult to access and irradiated area. In order to improve the robustness and the performance of the gas flow control, flowmeters will be added during the first long shutdown of the LHC in 2013-2014. As these flowmeters cannot operate in a radiation environment they have to be located in safe areas located up to 50 m away from the current leads. It is planned to keep the control valves next to the current leads because moving them next to the flowmeters would require a heavy re-cabling operation. Due to the limited differential pressure available in the LHC (100 mbar) for the current lead gas flow, a diameter of 15 mm was chosen for the piping between the valves and the flowmeters. This diameter limits the pressure drop below 5 mbar for a gas flow of 0.06 g/s but it creates a buffer volume of about 9 liters between the valve and the flowmeter that could introduce a delay for the control of the mass flow. The typical reaction time needed to control the current leads is about 10 s. The goal of this study was to determine, both theoretically and experimentally, the effect of the buffer volume and of the measuring system on the control dynamics. A numerical model was developed and tests were performed on a test bench that was previously used for the calibration of the control valves [3]. Based on the measured characteristics, a PID control loop was optimized on the simulated model and was then applied to the test bench for comparison with the requirements for regulation of the current leads.

EXPERIMENTAL INVESTIGATION

Experimental setup

Figure 1 shows a schematic view of the experimental setup: gaseous helium is supplied by a 200 bar cylinder and a pressure regulator that reduces the pressure to 1.5 bar abs. This gas if fed into a 500 liter buffer volume whose pressure is regulated by CV1 at 1.1 bar, simulating the differential pressure conditions of LHC. From this buffer, the gas passes through the current lead regulation valve CV2 and then through 100 m of smooth tube with an inner

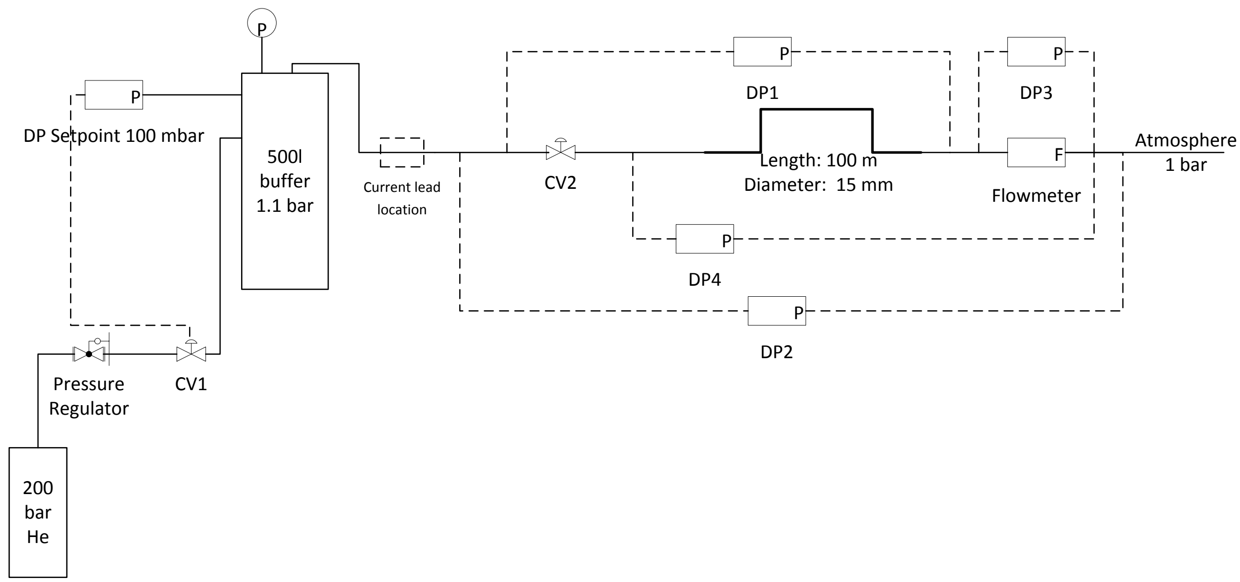

FIGURE 1. Schematic view of the test bench for research on the current leads dynamics

diameter of 15 mm. The length of 100 m was chosen as a worst case scenario with respect to the expected 50 m in the LHC. The mass flow was measured by a thermal mass flowmeter. This type of flowmeter is representative of the type of flowmeters that is the most likely to be installed in the LHC as it offers both a good precision and excellent reliability without any moving part. The pressure is measured at four positions by four pressure sensors (DP1 to DP4 on Figure 1) with a response time smaller than 100 ms, including the data acquisition system. The differential pressure across the flowmeter (DP3) provides an estimation of the mass flow through the flowmeter that is much faster than the thermal flowmeter itself. The data acquisition rate was 10 Hz. All measurements were performed at a helium temperature in the range of 293 K – 295 K.

The typical mass flows required by the current leads are 0.02 g/s for the 120 A current leads and 0.06 g/s for the 600 A current leads, so a maximum mass flow of 0.08 g/s was used for the measurements. The valve CV2 is a DN1.8 proportional valve with a Kv of 0.087 m^3/s, its characteristics is approximately linear op to an opening of approximately 70% [3], for the purpose of this study it is simulated with a linear characteristic. As the pressure across the valve CV2 varies only by about 10% over the investigated flow range, the flow through the valve (and through the current lead) is essentially proportional to the valve position.

Dynamic behaviour

The system dynamics was investigated by performing a series of steps with the valve CV2 in two configurations: without the 100 m tube (Figures 2.a, 2.b and 2.c) and with the tube (Figures 2.d, 2.e and 2.f) between the valve and the flowmeter.

In order to differentiate between the hydraulic dynamic behaviour and the response of the flowmeter a series of measurements was first performed without the tube. The steps used for the measurement are shown in Figure 2.a. The flow measured by the mass flowmeter (Figure 2.b) shows a time constant of 2.6 s while the time constant measured on the pressure drop DP3 (Figure 2.c) is 0.22 s.

In order to investigate the effects of the long tube, the sequence of steps (Figure 2.d) was repeated with the 100 m tube installed in the circuit. The time constant of the flow measured by the flowmeter (Figure 2.e) increased to 3.0 s, while the time constant of the differential pressure increased to 0.82 s.

Figure 3 shows a comparison between the response of the system with and without a tube for a valve step from 40% to 50%. The response of the flowmeter (Figure 3.a) and of the differential pressure (Figure 3.b.) was measured. From the moment a step is done with the valve CV2, the flowmeter takes around 0.57 seconds to start reacting (Figure 4) while the pressure sensor takes around 0.35 seconds.

From the measurements it clearly appears that the dynamic behaviour is dominated by the time constant of the flowmeter of approximately 2.6 s while the buffering volume of the pipe is responsible for about 0.5 s.

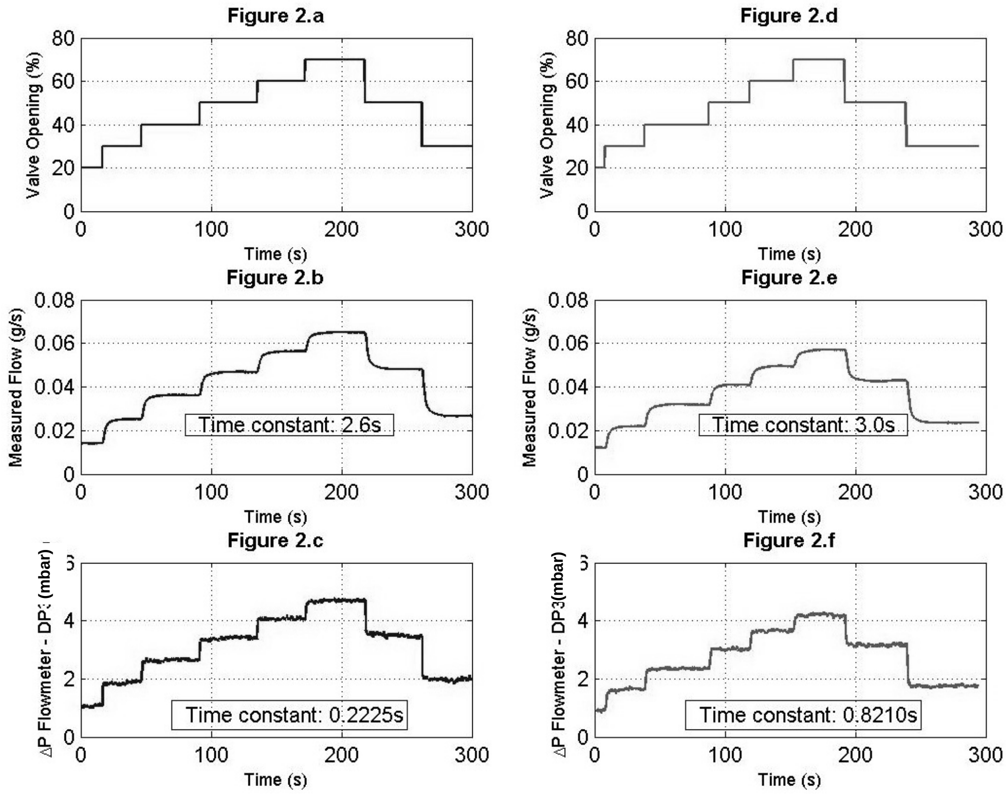

FIGURE2. Test bench dynamic results without tube (a, b, c) and with tube (d, e, f)

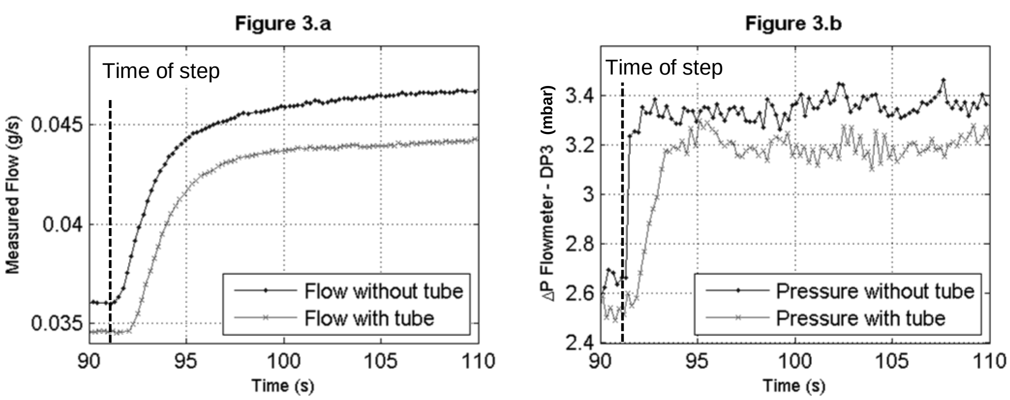

FIGURE 3. Comparison between dynamics measured with the flowmeter (a) and with the pressure difference (b)

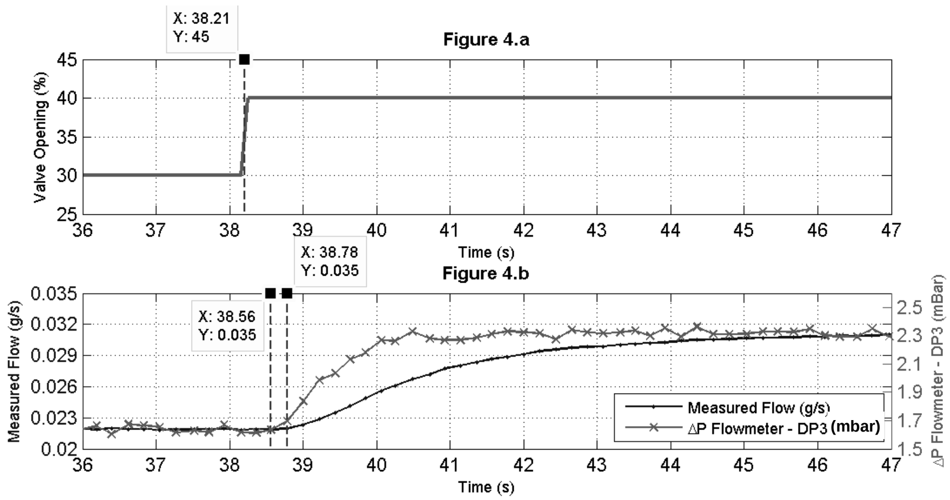

FIGURE 4. Zoomed view of the system dynamic response

SIMULATION MODEL

Model description

A numerical model of the system was developed with the Matlab Simulink® (R2010b) software. The system was modeled with the simplified scheme shown in Figure 5. The inputs variables are the size of the valve (Kv), the length of the tube (L) , the diameter of the tube (d), the input pressure (P_{IN}) and the output pressure (P_{OUT}), as well as the physical properties of the gas: Gamma ($\gamma = Cp/Cv$), Molar Mass (M), Density (ρ) and Viscosity (η).

FIGURE 5. scheme of the simulation model. CV891 corresponds to CV2 of Figure 1

Modeling the control valve (CV2)

The gas flow $\dot{m}$ through the valve with a flow area A is calculated with equations (1a) and (1b) [4].

$$\dot{m} = A\sqrt{2\,Y\,\rho\,(P_{IN} - P_{OUT})} \tag{1a}$$

$$where\ Y = \frac{\gamma}{\gamma - 1}\frac{(P_{OUT}/P_{IN})^{\frac{2}{\gamma}} - (P_{OUT}/P_{IN})^{\frac{\gamma+1}{\gamma}}}{1 - P_{OUT}/P_{IN}} \tag{1b}$$

Modeling the tube

The tube is modeled as a buffer volume filled with an ideal gas with varying pressure (starting at P_0 at time t =0 s) according to equation (2).

$$P = P_0 + \frac{R\,T}{M\,V}\int(\dot{m}_{IN} - \dot{m}_{OUT})dt \tag{2}$$

The pressure drop along the tube is also taken into account according to equation (3):

$$\Delta P = \frac{128.\eta.L}{\pi\ \rho\ d^4}\ \dot{m} \qquad (3)$$

Modeling the flowmeter

The model for the flowmeter includes a time constant of 2.6 seconds and a dead time of 0.57 seconds. The pressure drop across the flowmeter is also included.

The time constant with dead time is modelled by the following transfer function (Laplace domain):

$$TF(s) = \frac{e^{-0.57s}}{2.6s + 1} \qquad (4)$$

From the measured data, the pressure drop across the flowmeter varies linearly with the mass flow with a an experimental slope of 73.6 $\frac{mbar}{g/s}$.

Validation of the model

The model was run using the same valve openings and parameters as those used in the sequence of Figure 2.a and Figure 2.d. The graphs of Figure 6 compare the values obtained in simulated and real tests. Figure 6 shows that the model accurately reproduces the dynamic behaviour of the system. The small discrepancies on the absolute values of the flows are due to the fact that the valve is simulated by a linear function while in reality the valve characteristic is not perfectly linear at the maximum opening range [3].

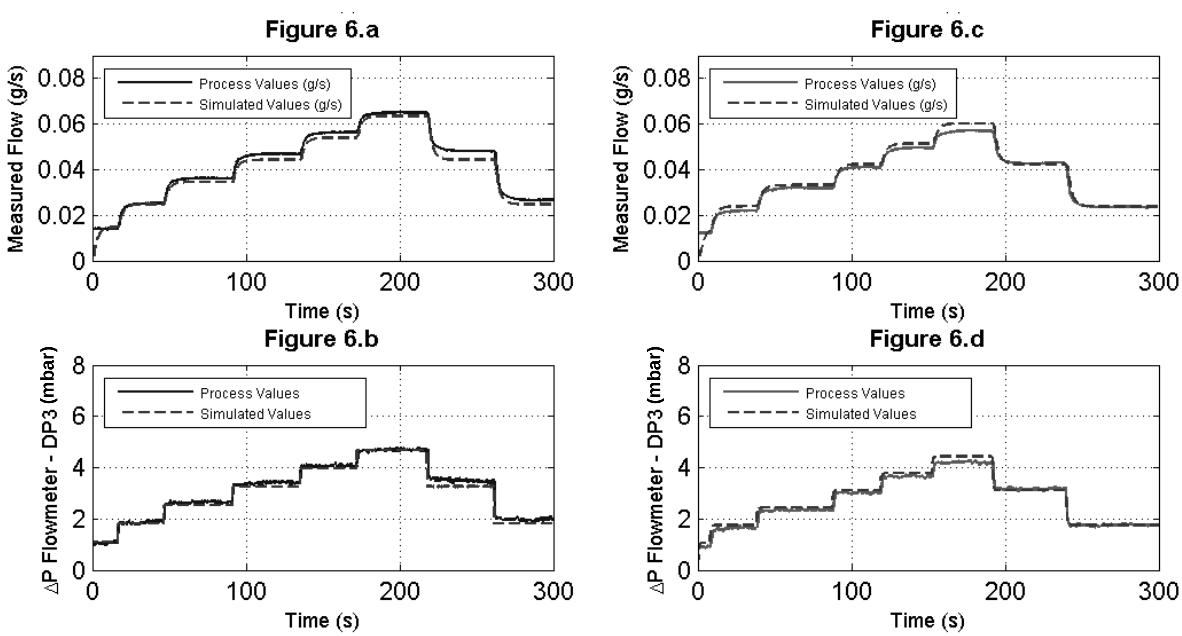

FIGURE 6. Comparison of Simulated Values with Real Values for configurations without (a, b) and with tube (c, d)

SIMULATION AND VALIDATION OF A CLOSED LOOP REGULATION

During the operation of the LHC, the mass flow will be set as function of the current trough the current leads. The mass flow value will be used as the set point for a PID closed loop control. As observed on Figure 2.e, the time constant of the system valve + tube + flow meter is about 3 seconds, mainly dominated by the time constant of the flowmeter. The transfer function of the system can be approximated to a first order with a dead time. The gain of this transfer function is given as the amount of helium that flows as a function of the valve position:

$$TF_{SYSTEM}(s) = 8.43 * 10^{-4} \frac{e^{-0.57s}}{3.0s + 1} \tag{5}$$

The closed loop regulation strategy is shown on Figure 7. Whenever there is a difference between the flow's set point and its measured values, the PID will adapt the valve position.

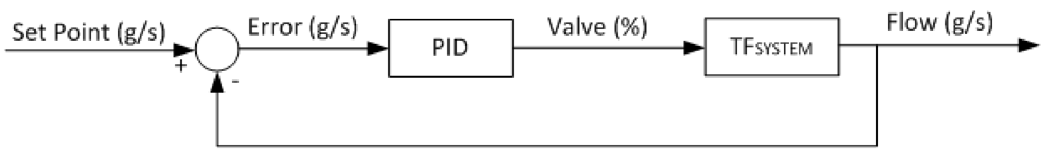

FIGURE 7. Closed Loop Control

The most common way of regulating a first order stable process without dead time is by using only proportional and integral factors (PI). If we consider that the effect of the dead time of this system can be neglected, then a PI control may work well as a control strategy. A simple solution for choosing the proportional (K_P) and integral (K_I) parameters is by using the Pole-Zero-Cancellation technique for a system with time constant θ and gain K:

$$K_P = \frac{\theta}{\tau * K}, K_I = \frac{1}{\tau * K} \tag{6}$$

The closed-loop transfer function of the system should theoretically be first order with gain 1 and a time constant τ (Eq. 7). However, as in reality there is dead time on the system, some oscillations of the output response are to be expected. The value of τ is free to be chosen but it can't be too different from θ, otherwise the regulation becomes an "on-off" control.

$$TF_{CL} = \frac{1}{\tau s + 1} \tag{7}$$

The parameters calculated with the above equations were applied to a PI regulation loop on the numerical model and on the test bench. A value of 3 s was chosen for τ (the same value as the system's time constant), as the objective is to have a stable closed loop control rather than a very fast reacting system prone to instabilities. Figure 8 shows the results for the closed loop control on the simulated model and on the test bench.

Figure 8.a shows the response to a step in the flow set point that is representative of the variations expected during operation. The measured flow reaches stable conditions within 8 second and is within 5% of the set point in about 3 s. Figure 8.b shows the pressure drop across the flow meter: an overshoot of the real flow is present while that is not visible when measured with the flowmeter because of its time constant. The valve opening, (which gives an estimation of the flow through a lead) (figure 8.c) shows also an overshoot and then stabilizes within 8 seconds.

For set points outside of the range where the control valve is well linear (approximately up to 0.05 g/s) the simulation deviates significantly from the actual measurements as shown in Figure 8.c and Figure 8.d.

As a reaction time of about 10 s is required to control the leads, the results show that the proposed configuration, with a thermal mass flowmeter and up to 100 m long tube can be used to control the gas flow.

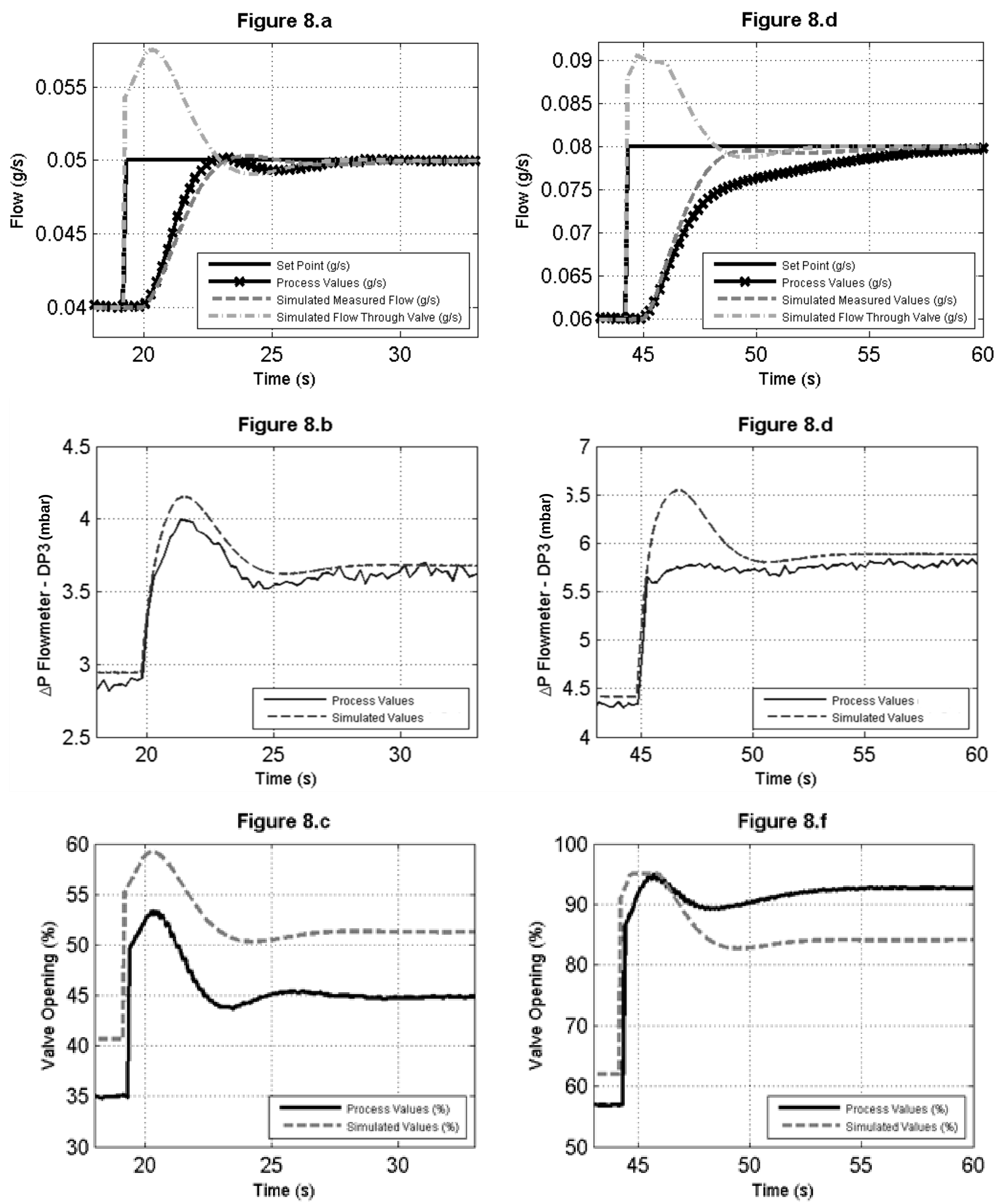

FIGURE 8. Comparison of simulated values with real values in closed loop for configuration with tube for two flow ranges

CONCLUSIONS

The effect of a 100 m long, 15 mm diameter tube between a control valve and a flowmeter was determined for flows typical of 120 A and 600 A resistive gas cooled current leads (between 0.02 g/s and 0.06 g/s). The dynamic behaviour of the system was found to be dominated by the thermal mass flowmeter measuring system, with a typical total time constant of 3 s of which approximately 2.5 s are due to the flowmeter and approximately 0.5 s are due to the effect of the 100 m long tube. A model was developed to allow the study of the dynamic behaviour of the system and it was successfully validated by comparison with physical measurements.

The parameters of a PID closed loop regulation system were determined thanks to the model and to the measured data. The regulation loop was then tested on the numerical model and on the test bench, showing that the investigated configuration is compatible with the control of the gas flow for the current leads of the inner triplets of LHC.

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