DESIGN OF A FEEDBACK CONTROL SYSTEM FOR REAL-TIME CONTROL OF FLOW IN A SINGLE-SCREW EXTRUDER

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Abstract: A closed loop controller is designed for regulation of the volumetric output flow in a polymer extruder. To this aim, temperature and pressure at the machine output must be controlled on the basis of real time measurements. It has been verified that temperature and pressure regulations can be achieved by solving two disjoint control problems. The temperature controller acts on the heat delivered to the plastic material by the heater electric resistance bands on the barrel; the pressure controller uses as a control action the voltage applied to the screw electrical engine in order to obtain real time modulation of the screw revolution speed. The designed control system shows very good performances in regulation of the flow output and good robustness properties to variations in the operating conditions and the material properties.

Keywords: Extrusion, Polymer processing, Cascade control

1. INTRODUCTION

Polymer extrusion is a very important process in the plastic industry. The extrusion process has a standard setup including a feeding section, a barrel and a head, including a die for shaping. In the feeding section, the polymer is fed into the extruder through a hopper in the form of pellets, if pure new material is used or in the form of irregular small bits, when using recycled material. Then, the polymer is transported along a barrel through different zones by means of the screw action. In the barrel the material is compacted and melted and pushed towards the die where the extruded final product is expelled.
During the process, the material undergoes very complex thermo-mechanical transformations inducing strong changes in the physical properties of the material. These are basically dependent on the pressure and temperature changes in the extruder.
The output of an extruder almost always exhibits periodic fluctuations, mainly depending on internal flow instabilities. Often, the amplitude of such fluctuations could be large enough to induce undesirable negative effects on the quality of the final product (Mudalamane and Bigio, 2003; Costin et al., 1982a, 1982b; Wellstead et al. 1998; Broadhead et al., 1996). In fact, small variations of the die pressure and temperature could result in large variation of the throughput flow (Maddock, 1964).
In this paper, a prototype of a feedback automatic control system for real time control of the output flow in a Single Screw Extruder (SSE) is presented. This

work is the result of a joint research project (funded by Promaplast srl) including the University of Bergamo (Italy), the Politecnico di Milano (Italy) and the CESAP (European Centre for the Development of Plastic Applications), Zingonia (Italy). Polymer output flow regulation is achieved by regulation of the pressure and temperature of the material at the output of the extruder, where a temperature sensor and a pressure transducer have been placed. The sensors are positioned so that they are in contact with the polymer. The measurement signals from the sensors are sent to a PC where they are conveniently filtered and conditioned. The control algorithm, implemented on the PC, sends the control signals to the extruder actuators. These are the electrical engine which drives the screw (for pressure regulation) and the resistance heater bands which heat the material inside the extruder (for temperature regulation).
The paper is organized as follows: in Section 2, the experimental setup is outlined. Specifically, the SSE used in this project is described and the control problem statement is proposed. Also, the sensors, the actuators, and the procedure for signal filtering and conditioning are presented. Section 3 is devoted to the design of the pressure and temperature control algorithms. In particular, it is worth noting that temperature control is carried out by a cascade control strategy. So, two temperature control problems must be solved. Finally, in Section 4, results of some validation tests are described.

2. EXPERIMENTAL SETUP AND STATEMENT OF THE CONTROL PROBLEM

The aim of this work is the design of a regulator for closed loop control of the extruded polymer volumetric flow of the OMP T35 L/D 35 SSE at the CESAP laboratory in Zingonia (Italy) (Fig. 1).

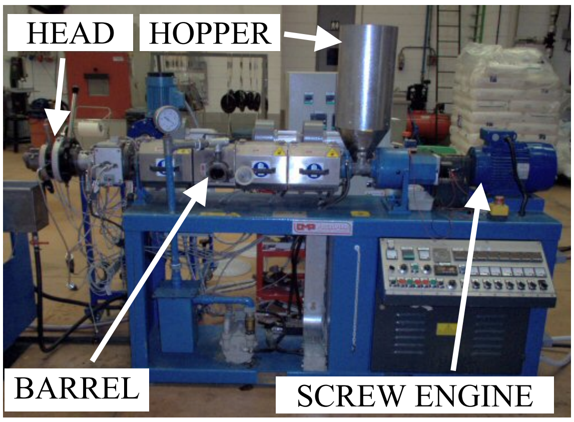

Fig. 1. The SSE OMP T35 L/D35 at the CESAP laboratory in Zingonia.

The extruder considered in the present work is endowed with seven electric resistance bands, in order to heat and melt the polymer. Specifically, the barrel has four heater bands and the head has three of them. The heaters can be switched on and off by means of electromechanical relays driven by PWM command signals with duty cycle $d_1,\ldots,d_7$, respectively. Each heater band has a temperature sensor (J-thermocouples with range from –40 °C to 333 °C). In the following, the temperature measurements from the heaters will be named T_1, …, T_7. The screw electrical engine is driven by an inverter whose command voltage V can be modulated between 0 V and 5 V corresponding to a screw revolution speed between 0 rpm and about 200 rpm. The screw revolution speed is measured by a unidirectional incremental encoder with maximum speed range of 5000 rpm and with a resolution of 250 pulses per revolution.
All the measured variables are sent to a data acquisition board on a PC with sixteen analog input channels. The temperature signal acquisition is performed at 1 Hz sampling rate. The pressure signal acquisition is performed at 10 Hz sampling rate. An analog output board with eight channels provide the command signals to drive the heaters and the screw engine. The PC is endowed with the operating system Microsoft Windows 2000 Professional® and all the control algorithms and signal filtering is performed by using National Instruments Labview®.
The output volumetric flow Q strictly depends on the material output pressure P_{out} and temperature T_{out} (Rauwendaal, 2001). Eq. 1 gives the dependence of the output flow from the material properties and the output pressure and temperature for a SSE:

$$Q = K_{out} \frac{\pi r_{out}^3}{\left(3+\frac{1}{n}\right)} \left(\frac{P_{out} r_{out}}{2Ae^{-BT_{out}} l_{out}} \right)^{\frac{1}{n}} \qquad (1)$$

In Eq 1, the parameters A, B, n are related to the physical properties of the polymer and they must be estimated from the rheological curves of the considered material. The parameters K_{out}, r_{out} and l_{out} are geometrical ones and they must be computed on the basis of the geometry of the head of the considered extruder.
So, the output volumetric flow can be computed on the basis of output temperature and pressure measurement. To this aim, a temperature sensor and a pressure transducer were placed in the extrusion head at about 10 cm from the output die. The temperature sensor was placed in the middle of the head section, while the pressure transducer was put at the contact interface between the metal and the material. In order to analyze the performance of the uncontrolled extruder, extrusion of polypropylene in standard operating conditions has been considered. Figs. 2.a and 2.b show time plots of the output temperature T_{out} and output pressure P_{out}. The polymer extrusion starts at about $t\approx 9$ min. Notice that there are evident oscillations in both temperature and pressure. In this specific experiment, temperature oscillations have a total amplitude of about 5 °C (about a mean value of 210 °C) and pressure oscillations have an amplitude of about 2 bar (about a mean value of 22 bar).

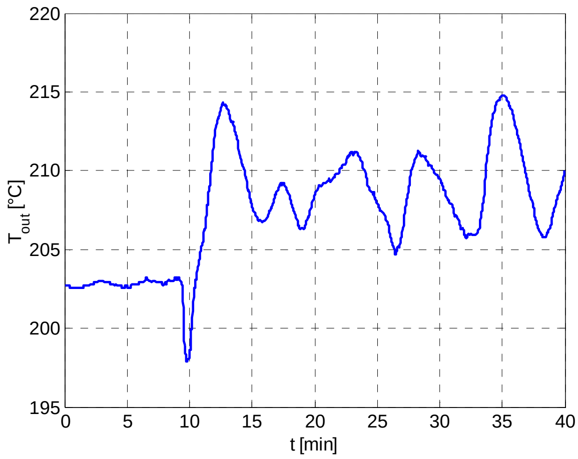

Fig. 2.a. Polypropylene temperature in the extrusion head. Extrusion starts at $t\approx 9$ min. Temperature oscillations between about 205 °C and 215 °C are clearly evident.

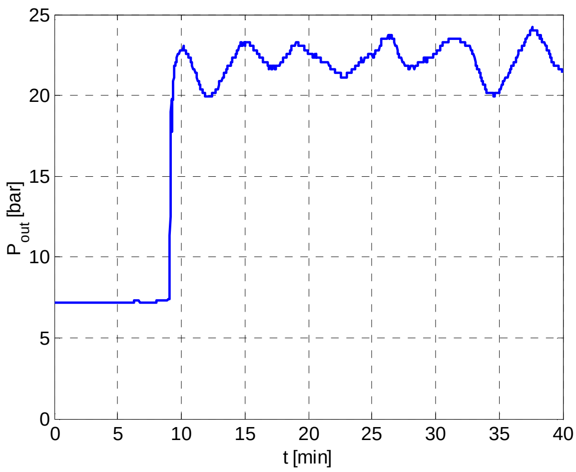

Fig. 2.b. Polypropylene pressure in the extrusion head. Extrusion starts at $t\approx 9$ min. Pressure oscillations between about 20 bar and 24 bar are clearly evident.

Temperature and pressure oscillations have negative effects on the quality of the final product and the extruded polymer has highly irregular thickness. This is a well known problem in literature (see Rauwendaal, 2001; Mudalamane and Bigio, 2003 for example).
Sensitivity analysis performed on Eq. 1 allows the computation of the flow changes as a consequence of unitary changes in the temperature and pressure values. The output flow, about standard operating conditions, changes almost linearly of about 2% for each Celsius degree variation in the temperature. Similarly, the output flow changes of about 3% for each percent of variation in the pressure. So, considering the oscillation amplitudes evidenced in Figs. 2.a e 2.b, it is possible to argue that, in nominal operating conditions, the output flow could have large undesired variations, up to 30% as a consequence of pressure oscillations and up to 10% as a consequence of temperature oscillations. In order to achieve output flow regulation, it is necessary to control the output temperature T_{out} and the output pressure P_{out}. Specifically, controlling the temperature and the pressure at a desired nominal constant value, it is expected that also the polymer output flow will be constant, avoiding undesired flow variations and increasing the quality of the final product. So, in conclusion, the flow control problem reduces to a joint temperature T_{out} and pressure P_{out} control problem. The available control actions are the duty cycles d_1, …, d_7 of the PWM command signals of the seven heater bands and command voltage V of the screw engine inverter (Fig. 3).

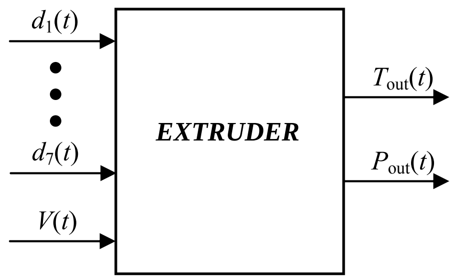

Fig. 3. Schematic representation of the extruder with the control variables $d_1(t)$, …, $d_7(t)$, $V(t)$ and the measured controlled variables $T_{out}(t)$ and $P_{out}(t)$.

3. CONTROL SYSTEM DESIGN

The output pressure $P_{out}(t)$ mainly depends on the screw revolution speed, which is driven by the inverter command voltage $V(t)$. Similarly, the output temperature $T_{out}(t)$ mainly depends on the heat delivered by the heaters, i.e. it depends on the duty cycles signals $d_i(t)$, i=1, ...7. However, it is well known in extrusion practice that any modification in the screw revolution speed also influences the temperature profile along the extruder and, similarly, any change in the heat quantity delivered to the polymer has visible effect in the output pressure value. In the present case, it has been noticed that this cross-influences are very small. So, the two control problems (pressure and temperature regulations) have been solved separately as shown in Fig. 4. According to this decoupled approach, influence of heat delivery on pressure (or of screw speed on temperature) can be seen as disturbances that must be compensated by the pressure controller (or by the temperature controller). The correctness of this hypothesis will be verified in the result section.

3.1 Temperature controller design

Each heater band of the extruder is endowed by the producer with a local control loop. So, temperature control can be achieved by means of a cascade strategy, involving the use of two nested control loops. The inner loop is composed by seven controllers devoted to the regulation of the local temperature of each single heater. The outer controller decides the set-points for the inner loop in order to keep the temperature T_{out} at the desired value (see Fig. 5). Notice that (see Fig. 5) the set-points of the inner loops are set at the same value, although it is possible, in principle, to use a different set-point for each heater band.

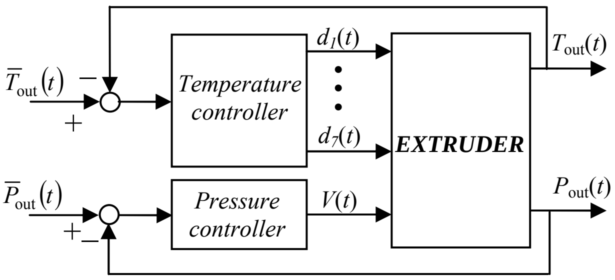

Fig. 4. Schematic representation of the decoupled control system for temperature and pressure regulation. The variables $\overline{T}_{out}(t)$ e $\overline{P}_{out}(t)$ are respectively the temperature and pressure set-points. The two regulators, on the basis of real time measurements of the pressure $P_{out}(t)$ and the temperature $T_{out}(t)$, decide the value of the control variables $d_i(t)$ (the heaters) and $V(t)$ (the screw), so that the controlled variables track the set-point values.

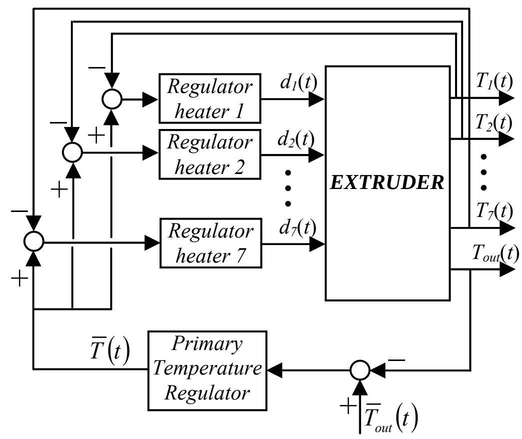

Fig. 5. Schematic representation of the temperature cascade control strategy.

<u>*Design of the local temperature controller for the heater resistance bands*</u>. First, seven controllers for the heater resistance bands must be designed. The built-in local temperature controllers, designed by the manufacturer, provide unsatisfactory performances. An example of the behaviour of such a controller during polypropylene extrusion in standard operating conditions is shown in Fig. 6. The heater band considered in this example is the first one on the barrel (T_1). The temperature set-point is 210 °C (dotted line). The measured temperature (dot-dashed line) has evident undesired oscillations of very high amplitude. Moreover, a regulation offset is clearly visible. So, a set of new local regulators, one for each heater band, has been designed, excluding the built-in controller. Each local regulator keeps the temperature of each heater band at the desired set point. Each regulator must decide the duty cycle $d_i(t)$ for the corresponding switching electromechanical relay, so that the measured temperature $T_i(t)$ tracks the reference $\overline{T}(t)$. To this aim, seven PID controllers have been used. Each controller was tuned using the area method (Astrom and Hagglund, 2000) on the basis of a dynamic model of the relationship between $d_i(t)$ and $T_i(t)$. The model was estimated on the basis of step response data and using a first order plus delay model.
As an example, consider the first heater band. The transfer function $F_1(s)$ from $d_1(t)$ to $T_1(t)$ is:

$$F_1(s) = \frac{T_1(s)}{d_1(s)} = \frac{935.5}{1+1644s} e^{-146.8s} \qquad (2)$$

On the basis of the model of Eq. (2) the controller parameters have been tuned. Again considering the first heater as an example, the parameters of the controller are: proportional gain $K_p = 0.0144$; integral time $T_i = 293.6$; derivative time $T_d = 73.4$. Finally, the controller has been digitally implemented and applied to the heater. Fig. 6 shows a comparison between the performance of the original built-in controller and the new designed one. Setting the temperature set-point for the first heater at $\overline{T}_1(t) = 210$ °C (dotted line), the temperature $T_1(t)$ with the original controller has evident oscillations (dot-dashed line), with a large offset error. The new controller (solid line) definitely overperforms the previous one.

<u>*Design of the primary temperature controller*</u>. The aim of the primary temperature controller is the regulation of the measured temperature $T_{out}(t)$ of the extruded polymer. On the basis of this measurement the controller decides the set-point $\overline{T}(t)$ to be fed to the seven local heater band control loops. Notice that, in the proposed control strategy, the set-point $\overline{T}(t)$ is the same for all the local control loops.
The design procedure for the primary controller is the same used for the local controllers design. First a dynamic model of the relationship between $\overline{T}(t)$ and $T_{out}(t)$ is estimated on the basis of step response data and using a first order plus delay model. Then, a PID controller is tuned using open loop Ziegler and Nichols rules (Astrom and Hagglund, 2000).
The model transfer function $G_T(s)$ is:

$$G_T(s) = \frac{T_{out}(s)}{\overline{T}(s)} = \frac{0.99}{1+472.61s} e^{-144.15s} \qquad (3)$$

The tuned parameters of the PID controller are: proportional gain $K_p = 3.9741$; integral time $T_i = 287.98$; derivative time $T_d = 72.07$. Finally, the controller has been digitally implemented and applied to the plant. Results about the performance of the designed control system are reported in Sect. 4.

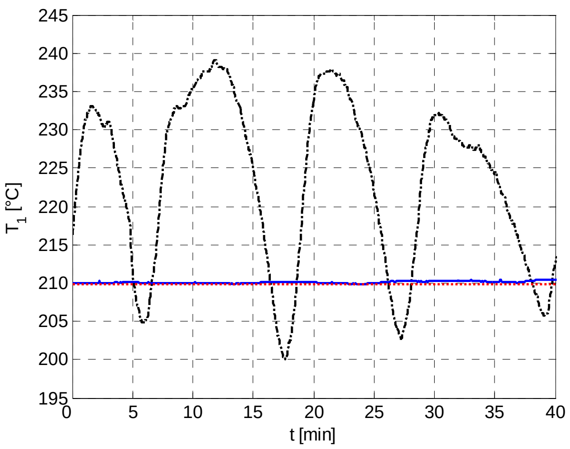

Fig. 6. Heater band 1. Comparison between the performance of the old controller (dash-dotted line) and the new one (solid line). The temperature set-point is 210 °C (dotted).

3.2 Pressure controller design

The task of the pressure regulator is to decide the screw engine inverter command voltage $V(t)$ so that the output polymer pressure measurement $P_{out}(t)$ tracks the assigned pressure set-point. The controller, acting on the inverter, modifies the screw revolution speed which directly influences the polymer pressure in the extruder.

First of all, a model of the relationship between the voltage $V(t)$ and the measured pressure $P_{out}(t)$ has been estimated on the basis of step response data. The transfer function $G_p(s)$ is:

$$G_p(s) = \frac{P_{out}(s)}{V(s)} = \frac{4.9}{1+1.2028s} e^{-0.1472s} \qquad (4)$$

On the basis of the estimated model, the parameters of a PID controller have been tuned using the area method (Astrom and Hagglund, 2000). The controller parameter values are: proportional gain $K_p = 2.0011$; integral time $T_i = 0.2946$; derivative time $T_d = 0.07356$. Finally, the controller has been digitally implemented and applied to the plant. Results about the performance of the designed control system are reported in Sect. 4.

4. RESULTS

In this section, results about the application of the pressure and temperature controllers designed in the previous section will be presented. Many tests have been performed on the closed loop controlled extruder. The test results show that the controllers are able to regulate very accurately the polymer output temperature and pressure at constant values and that the system is robust against unexpected variations in the material quality and the operating conditions. Here, for the sake of brevity, results about the behaviour of the closed loop system when the pressure set point $\overline{P}_{out}(t)$ is step changed (Figs. 7.a, 7.b). Notice (Fig. 7.a) that the pressure regulation is very fast (settling time lower than 2 minutes) and the steady state error is lower than about 1 bar, that is about 5% in the considered test. In Fig. 7.a the revolution speed of the screw is also reported. In Fig. 7.b, it is shown that the temperature doesn't change during the test. This shows that the temperature controller reacts correctly to changes in the plant.

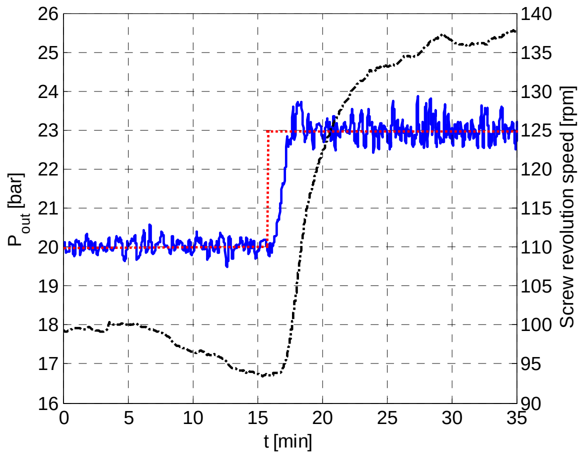

Fig. 7.a. Behaviour of pressure $P_{out}(t)$ (solid line) as a consequence of a step variation in the set point $\overline{P}_{out}(t)$ (dotted line). The controller increases the revolution speed of the screw (dash-dotted line) to increase the pressure, as requested.

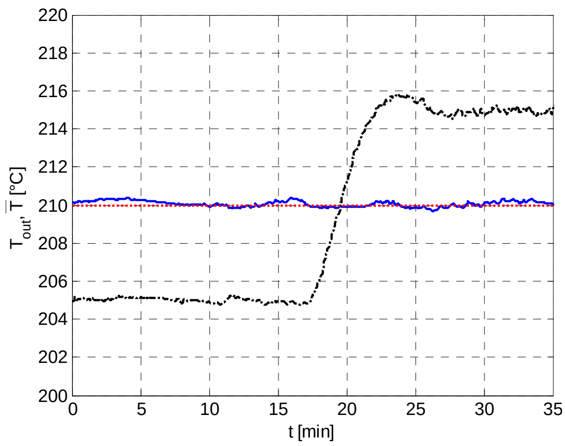

Fig. 7.b. Temperature $T_{out}(t)$ (solid line) during the pressure step variation test. The temperature set point is $\overline{T}_{out}(t)=210$ °C (dotted line). The temperature controller is able to keep constant the output temperature value by responding to pressure variation with a modification in the local temperature set points (dash-dotted line).

The third test (Figs. 8.a, 8.b) is dual with respect to the previous one. It shows the behaviour of the automatic control system responding to a step variation in the temperature set-point $\overline{T}_{out}(t)$. Fig. 8.a shows that the temperature regulation is fast and accurate, with settling time lower than 10 minutes and steady state error lower than 1 °C. Fig. 8.b shows that the pressure regulation is effective in rejecting the effect of the temperature set point variation. In fact, the automatic controller increases the screw revolution speed in order to keep the pressure constant regardless of the temperature variation.

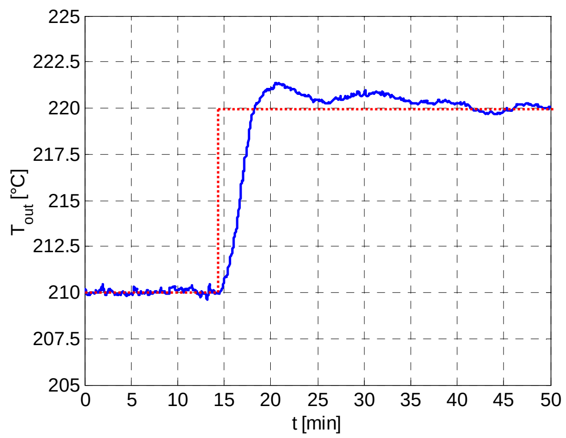

Fig. 8.a. Temperature $T_{out}(t)$ (solid line) following a step variation of the temperature set point $\overline{T}_{out}(t)$ (red dotted line).

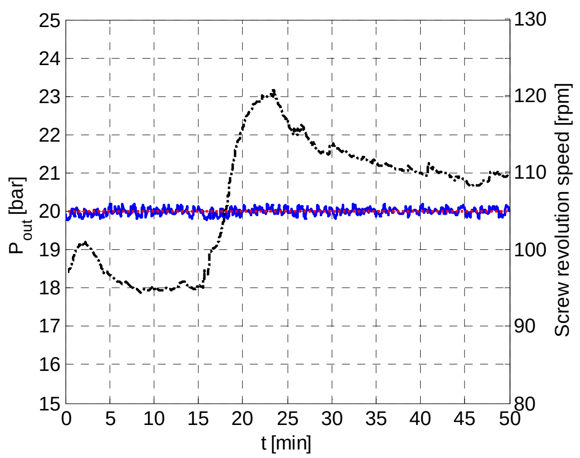

Fig. 8.b. Behaviour of the pressure $P_{out}(t)$ (solid line) as a consequence of a step variation in the temperature set point $\overline{T}_{out}(t)$. The pressure set point is $\overline{P}_8(t) = 20$ bar (red dotted line). The screw revolution speed (dash-dotted) increases to keep constant the pressure value, rejecting the temperature disturbance.

5. CONCLUSIONS

In this work a prototype feedback control system for real-time regulation of temperature and pressure of the material in an extruder has been designed and experimentally tested.

Real-time regulation of temperature and pressure has been effectively achieved by using standard PID control algorithms. The performance of the control system can be considered satisfactory from all points of view: the system reacts rapidly to changes in the operation conditions and effectively rejects disturbances due to changes in the quality of the material; the regulation achieved provides very small steady state errors both for pressure and temperature.

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