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Design of a feedback control system for real-time control of flow in a single-screw extruder

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Abstract

The topic of this paper is the design and experimental testing of a prototype feedback control system for the regulation of the volumetric flow in a polymer single-screw extruder. Flow regulation is achieved by means of joint regulation of the temperature and the pressure at the die. The overall controller architecture is constituted by three control sub-tasks: the inner-loop control of the local temperatures along the barrel; the outer-loop control of the temperature at the extruder output; the control of the pressure at the extruder output. In this work, the whole design procedure (modeling, controller design, and testing) is presented. Extensive tests have shown that the system reacts rapidly to changes in the operating conditions and effectively rejects disturbances due to unexpected changes in the quality of the material. The achieved regulation provides very small steady state errors both for pressure and temperature. Moreover, it is shown that this control system is a cost-effective alternative to mechanical volumetric pumps.

Keywords: Extrusion; Polymer processing; Closed-loop cascade control; Multi-variable control; Over-actuated system

1. Introduction

A continuously increasing number of commercial products are produced by polymer extrusion using plasticating extruders, which are among the most widely used equipments in polymer process industry.

The extrusion process has a standard setup including a feeding section, a barrel and a head with a die for shaping. In the feeding section, the solid polymer is fed into the extruder through a hopper in the form of pellets or irregular small bits. Then, the polymer is transported along the barrel by means of a rotating screw. The barrel wall is equipped with a number of electric heaters which melt the polymer. The material is melted and pushed towards the die where the extruded final product is shaped and expelled. During the process, the polymer undergoes very complex thermo-mechanical transformations inducing strong changes in the physical properties of the material.

A high-quality extrusion is essentially characterized by a precisely-regulated output volumetric flow; this can be achieved by finely regulating the temperature and the pressure of the die at the output of the extruder (Noriega, del pilar, & Rauwendaal, 2001).

Traditionally, the regulation of the output temperature and pressure is obtained by open-loop tuning of the rotating-screw speed and the electric heater set-points; this is usually done by an expert human operator. The current challenge is to develop a cost-effective fully-automatic regulation of the output flow, which can consistently guarantee high-quality product.

In the literature, a few works on identification and control of plasticating extruders have appeared (see e.g. Costin, Taylor, & Wright, 1982a for an overview). In (Kochhar & Parnaby, 1977) system identification

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methods are applied to the problem of modeling a single screw extruder; specifically, discrete time dynamic models of the dependence of the output temperature and pressure on the screw revolution speed are estimated from I/O data. Moreover, linearity of the extrusion process has been verified on a wide range of operating conditions. In Costin, Taylor, and Wright (1982b) the dynamic relationship between the screw speed and the output die temperature and the melt pressure (the pressure transducer was placed in the barrel before the head) has been empirically modeled, and a comparison between the performances of a PI controller and a self-tuning regulator for melt pressure control is provided. More recently, other related problems have been considered (see e.g. viscosity control in Broadhead, Pattwrson, and Dealy (1996); Chiu and pong (2000) and identification and control of the web formation processes during polymer film extrusion in Wellstead, Health, and Kjaer (1998)).

To the best of our knowledge, a detailed description of the overall control system for a plasticating extruder have never been proposed in the open literature. The goal of this work is to fill this gap, and to propose a comprehensive and detailed description of this control system.

Despite the inherent complexity of the system dynamics (an extruder is a spatially distributed system with large time delays) the overall control architecture proposed herein is constituted by three simple control sub-tasks: the inner-loop control of the local temperatures along the barrel; the outer-loop control of the temperature at the output; the control of the pressure at the output. This control architecture is simple, effective, and provide high-performance results; moreover, it is obtained by means of simple on-off electro-mechanical relays, and without the help of mechanical volumetric pumps.

This work focuses on a Single-Screw-Extruder (SSE). Specifically, it has been developed on the OMP T35 L/D 35 SSE, located at the CESAP laboratory (Fig. 1). This work is the result of a joint research project (funded by Promaplast s.r.l.) developed by the University of Bergamo (Italy), the Politecnico di Milano (Italy) and the CESAP (European Centre for the Development of Plastic Applications, Bergamo (Italy)).

The outline of the paper is as follows. In Section 2, the experimental set-up and the control problem is described. In Section 3 the modeling and control-design tasks are described. In Section 4 some experimental results are presented and discussed.

2. Experimental setup and problem setting

A SSE is mainly constituted by four main parts: the hopper, the screw engine, the barrel and the head. The

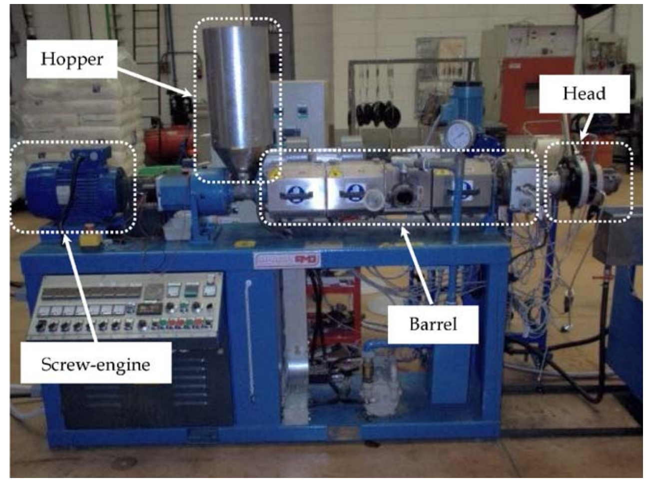


Fig. 1. The SSE OMP T35 L/D35 at the CESAP laboratory.

input/output variables of the system are the following (see Figs. 1 and Fig. 2):

Input variables (control variables):

- *Engine command (one variable).* The screw electrical engine is driven by an inverter whose command voltage V can be modulated in the range 0–5 V (corresponding to a speed range of about 0–200 rpm).
- *On-off heater relay commands (seven variables).* The SSE is equipped with seven heater bands. These are electric resistances which can be switched on and off by means of electromechanical relays. More specifically, four heaters are located in the barrel; three heaters in the head. In order to achieve a finely-regulated temperature, the on-off command of the relays has been converted into a PWM-signal, with a 5 s period. The input variables $d_1,\ldots,d_7$ henceforth are the corresponding duty-cycles of the PWM signals.

Output variables (measured variables):

- *Heaters temperature sensors (seven variables).* Each heater is equipped with a local temperature sensor (J-thermocouple with range from $-40\,^{\circ}$C to $333\,^{\circ}$C). The heater temperature measurements are named $T_1,\ldots,T_7$.
- *Output temperature sensor (one variable).* A temperature sensor is placed in the extrusion head at about 10 cm from the output die. The temperature sensor is a needle probe. The measured signal is named T_{out}.
- *Output pressure sensor (one variable).* The pressure transducer is placed at the contact interface between the metal and the material; the measured signal is named P_{out}.

All the I/O signals are sent to a PC-based standard I/O card. The system is multi-rate: the sampling time is 1 s for the temperature sensors and heaters relay

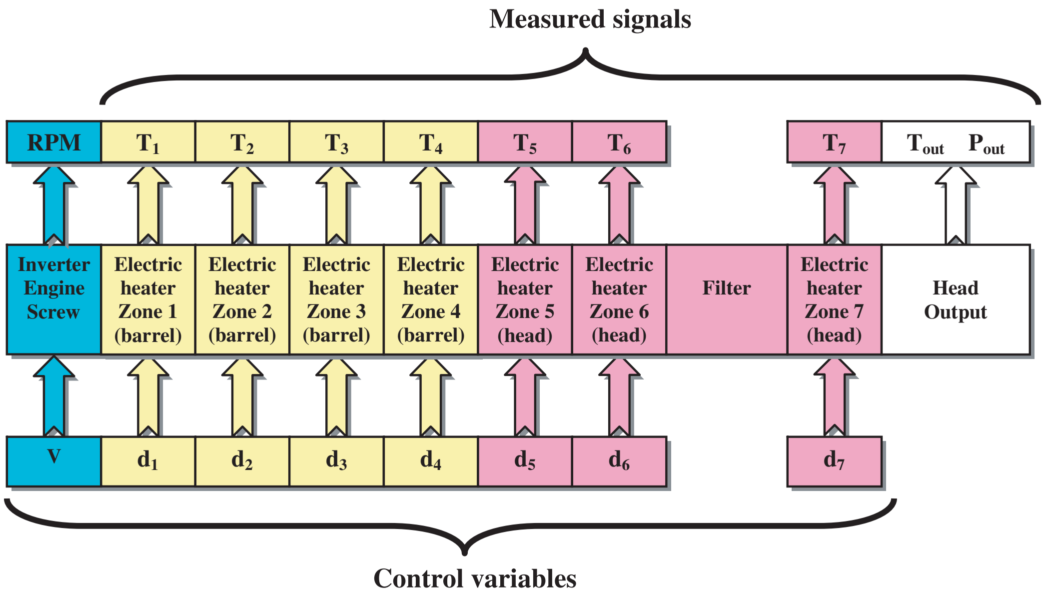


Fig. 2. Input/Output layout of the SSE.

commands; 0.1 s for the pressure sensor and the engine command. All the filtering and control algorithms are implemented on a PC using NI Labview®.

In order to understand the bulk of the control problem, it is interesting to inspect the general expression of the volumetric flow at the output of the extruder. It is approximately given by the following expression (Ranwendaal, 2001):

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

Notice that (1) is a static function, which depends on:

- physical properties of the polymer (parameters A, B, n).
- geometrical features of the head and the die of the extruder (parameters K_{out}, r_{out} and l_{out}).
- output temperature and pressure of the die (T_{out} and P_{out}, respectively).

Assuming that the rheological features of the polymer and the geometrical features of the extruder are fixed, the output flow simply depends on the output temperature and pressure.

As already said, the final control goal for an extruder is to finely-regulate the volumetric flow $Q(t)$, which cannot be directly measured; apparently, this control goal can be re-cast into a joint regulation problem of the output temperature T_{out} and of the output pressure P_{out}.

From (1), it is interesting to estimate the sensitivity of $Q(t)$ with respect to variations of T_{out} and P_{out}. Considering polypropylene in standard operating conditions (200 °C, 20 bar), simple computations show that the normalized variation of volumetric flow ($\Delta Q/Q$) is linked to the normalized variations of temperature ($\Delta T_{out}/T_{out}$) and pressure ($\Delta P_{out}/P_{out}$) as follows:

$$\begin{aligned} \frac{\Delta Q}{Q} &\approx 3.78 \frac{\Delta T_{out}}{T_{out}}, \\ \frac{\Delta Q}{Q} &\approx 3.04 \frac{\Delta P_{out}}{P_{out}}. \end{aligned} \tag{2}$$

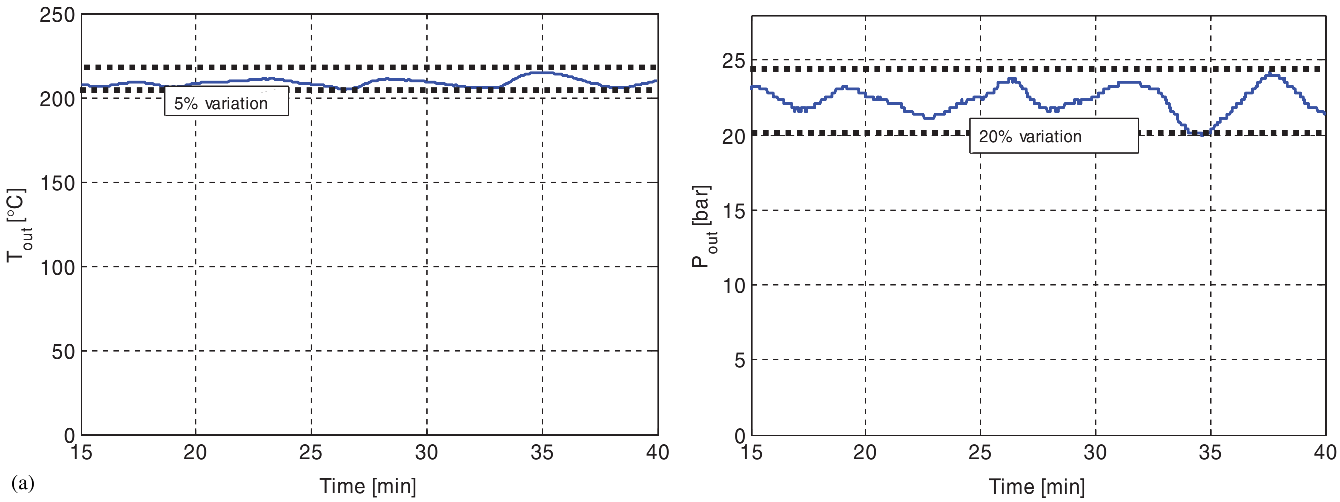
From (2), notice that the output flow is highly sensitive to variations of both temperature and pressure (e.g. 1% variation in T_{out} results in almost 4% variation in Q).

In order to understand better the typical flow variations observed in a standard extruder without feedback control, in Fig. 3 the behavior of T_{out}, P_{out}, and Q, during a 25-min experiment is displayed. From Fig. 3, notice that the variations of T_{out} are about 5% of the set-point; the variations of P_{out} are about 20% of the set-point; these variations result in a large 50% variation in the output volumetric flow.

These variations are due to many effects; the most important are:

- poor local temperature control of the on/off relays;
- disturbances due to environmental conditions;
- disturbance due to an irregular shape of the feeding material.

These oscillations have strong negative effects on the quality of the final product, since their result is an extruded polymer with irregular geometric properties. This is a well known problem in literature (Costin et al. 1982a,b; Fenner, Cox, & Isherwood, 1979; Mudalamane & Bigio, 2003; Noriega & Ranwendaal,



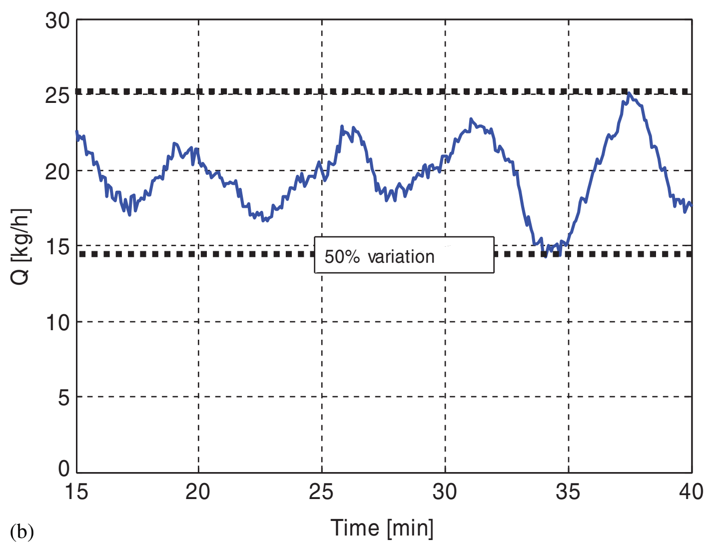


Fig. 3. (a). Output temperature (left) and pressure (right) (no feedback control—polypropylene extrusion). (b). Output volumetric flow (no feedback control—polypropylene extrusion).

2001; Ranwendaal, 2001). Good-quality extrusion requires that the volumetric variations remain in a 5% range; in high-precision applications this tolerance can be restricted to 1% (or even to 0.1%) variations.

3. Design of the control system

The general scheme of the controller architecture for the feedback regulation of the SEE is depicted in Fig. 4. Notice that the controller is characterized by the following I/O variables:

Controller inputs:

- reference (desired) values of the output temperature and pressure ($\bar{T}_{out}$and $\bar{P}_{out}$);
- measurement of the corresponding actual output temperature and pressure (T_{out} and P_{out});
- measurement of the seven local temperatures of the wall of the barrel and head (T_1,T_2,…,T_7).

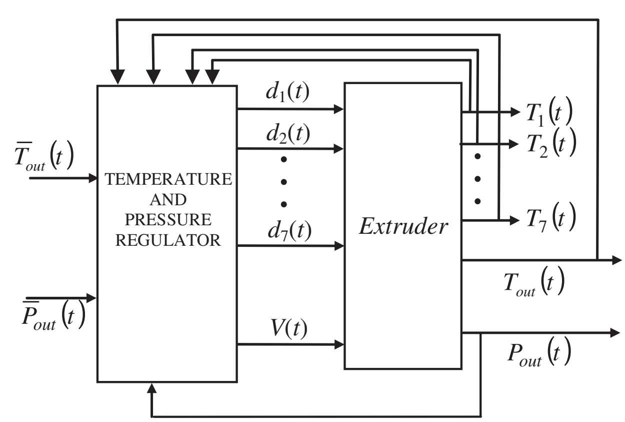


Fig. 4. General regulation scheme

Controller outputs:

- screw-engine inverter command voltage (V);
- PWM commands of the seven heaters (d_1,d_2,…,d_7).

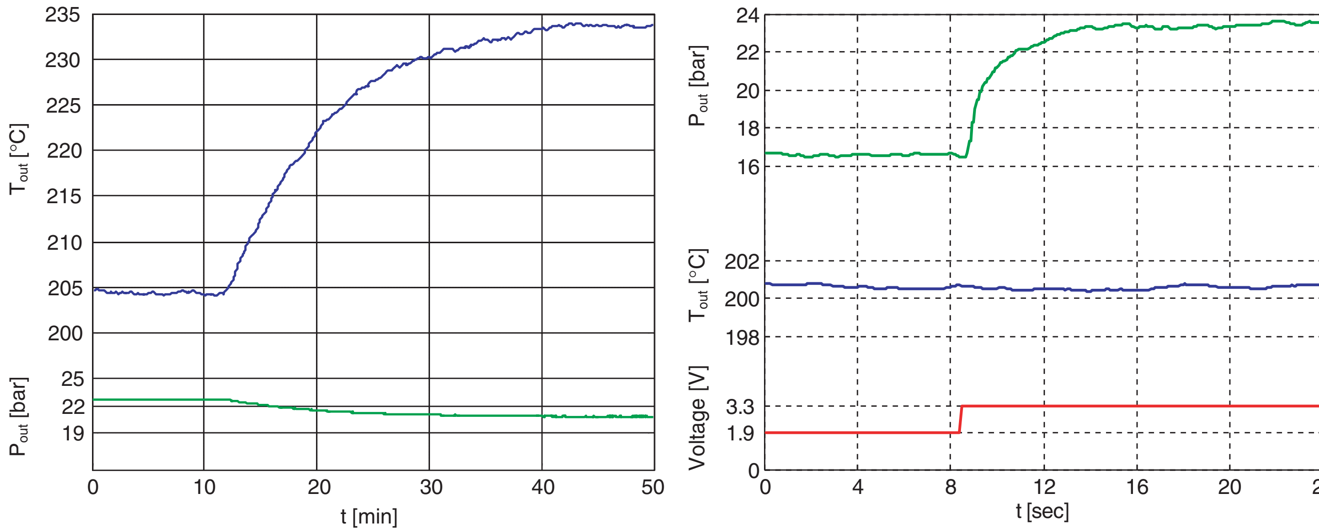


Fig. 5. Temperature and pressure responses to a step variation of the heater command signals (left), and to a step variation of the screw-engine inverter command voltage (right).

In principle, the internal structure of the controller in Fig. 4 can be very complicated: notice that the control problem is a multi-input-multi-output (MIMO) regulation problem of dimension 2, and the system is "over-actuated" (namely the number of control variables (8) is much higher than the number of controlled variables (2)). Also a non-linear control algorithm can, in principle, be required (see e.g. Guardabassi & Savaresi, 2001; Nijmeijer & Savaresi, 1998).

In order to simplify the controller structure, a simple preliminary experiment has been done: the SSE has been trimmed to a steady-state behavior, and single steps on the screw-engine inverter command voltage V, and on the PWM commands of the seven heaters (the same step have been applied simultaneously to all the heaters) have been applied. The results are displayed in Fig. 5.

From Fig. 5, the following conclusions can be drawn:

- The system is genuinely MIMO: a variation on V or on $d_1, d_2, \ldots, d_7$ significantly affects both T_{out} and P_{out} (notice that in the V-step experiment, T_{out} seems to be unaffected; this is simply due to the fact that the time-window displayed in Fig. 5 is very short).
- The dynamics of T_{out} and P_{out} are strongly frequency-decoupled: the settling tome of T_{out} is about 30 min; the settling-time of P_{out} is about 4 s.

Accordingly, the general control scheme of Fig. 4 has been strongly simplified; the proposed control scheme is illustrated in detail in Fig. 6. Notice that:

- According to the observed frequency-decoupled behavior, the regulation of T_{out} and P_{out} is achieved by means of two independent SISO loops.
- The over-actuation problem in the regulation of T_{out} has been solved by two nested control loops: the inner loop is constituted by seven identical local-temperature regulators; the outer-loop uses the set-point $\bar{T}$ of the inner-loops as control variable.
- The set-points $\bar{T}_1, \bar{T}_{2,\ldots,}\bar{T}_7$ of the seven inner loops can be simply set at the same value $\bar{T}$; however, notice that the control architecture proposed in Fig. 6 allows a static mapping $f(\cdot)$ for the relationships $\bar{T} \leftrightarrow \bar{T}_i$; in practice, it is convenient to set the reference of the first heaters at a slightly lower value (e.g. $\bar{T}_i = 0.95\bar{T}$); the reference of the heaters close to the head at a slightly higher value (e.g. $\bar{T}_7 = 1.05\bar{T}$). Once the $\bar{T} \leftrightarrow \bar{T}_i$ relationships are fixed, notice that the set-point of the seven heaters is condensed in a single variable $\bar{T}$.

In the rest of the section, the design of the three SISO control loops (pressure loop; inner temperature loop; outer temperature loop) will be briefly described and experimentally tested.

Control of the local temperature (inner loop)

The local-temperature control scheme is constituted by seven identical SISO control loops. The measured/controlled variable is the local heater temperature $T_i(t)$; the input (control) variable is the PWM duty-cycle $d_i(t)$; the reference signal is the desired value of the local temperature $\bar{T}_i(t)$ (as already pointed out, every $\bar{T}_i(t)$ is linked by a fixed relationship with $\bar{T}_i(t)$). Each local control loop is implemented with a classical PID structure (Astrom & Hagglund, 2000). The design of the PID has been done with a standard model-based indirect approach: the dynamic behavior of the relationship between $d_i(t)$ and $T_i(t)$ has been modeled and estimated from data (see e.g. Previdi & Lovera, 2003;

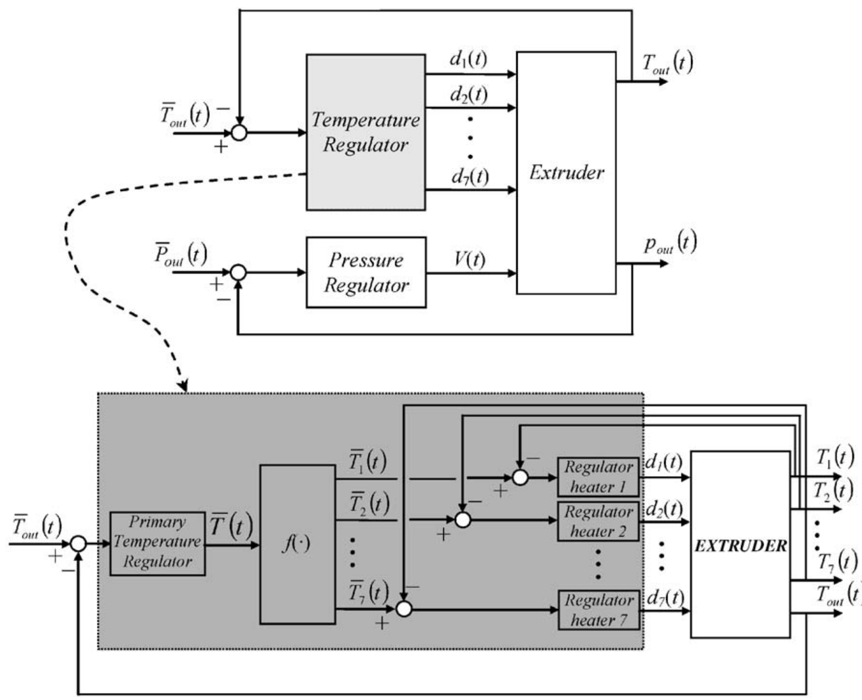


Fig. 6. Proposed architecture for the feedback control of the Single-Screw-Extruder.

Savaresi, Bitmead, & Dunstan, 2001; Savaresi, Bittanti, & Montiglio, 2005); the PID has been tuned by means of the estimated model (see e.g. Campi, Lecchini, & Savaresi, 2002; Previdi, Schauer, Savaresi, & Hunt, 2004).

As an example, consider the first heater band. The estimated transfer function $F_1(s)$ from $d_1(t)$ to $T_1(t)$ is:

$$F_1(s) = \frac{935.5}{1 + 1644s} e^{-146.8s}. \quad (3)$$

Eq. (3) describes the energy transfer from the electric resistance to the barrel walls. The transfer function parameters can be related to physical phenomena as follows:

- the *gain* represents the heat generation into the resistance by Joule effect. In fact, the heat generated is proportional to the input voltage at fixed current.
- the *pole* represents the internal energy variation of the barrel wall as a consequence of its temperature increase. So, the time constant is related to the thermal capacitance of the barrel wall into the first heater band.
- Notice that the *delay* is very short with respect to the time constant of the system. In fact, it does not have a genuine physical meaning. However, the delay is necessary to avoid the use of a higher order model to effectively describe the system step response at short times (See left side in Fig. 7).

On the basis of (3) the PID parameters have been tuned (proportional gain $K_p = 0.0144$; integral time $T_i = 293.6$; derivative time $T_d = 73.4$). Fig. 7 shows the quality of the estimated model, and the closed-loop performance. Notice that the new local-temperature controller strongly outperforms the old controller, and the large periodic oscillations have been removed (Bittanti & Savaresi, 2000; Savaresi & Wittenmark, 2000).

Control of the output temperature (outer loop)

The output-temperature control scheme is constituted by a SISO control loop. The measured/controlled variable is the output temperature $T_{out}(t)$; the input (control) variable is the set-point $\bar{T}(t)$ of the seven temperature inner-loops; the reference signal is the desired value of the output temperature $\bar{T}_{out}(t)$. Also this control loop is implemented with a classical PID structure, tuned with a model-based indirect approach. The estimated transfer function $G_T(s)$ from $\bar{T}(t)$ to $T_{out}(t)$ is

$$G_T(s) = \frac{0.99}{1 + 472.61s} e^{-144.15s}. \quad (4)$$

Eq. (4) is physical meaningful and the transfer function parameters can be easily understood as follows:

- the unitary *gain* is an obvious consequence of well-performing local temperature control loops.
- The *pole* represents the internal energy variation heater band walls and the polymer mass as a consequence of the temperature increase. Notice that this is a sort of mean value for all the heater bands.

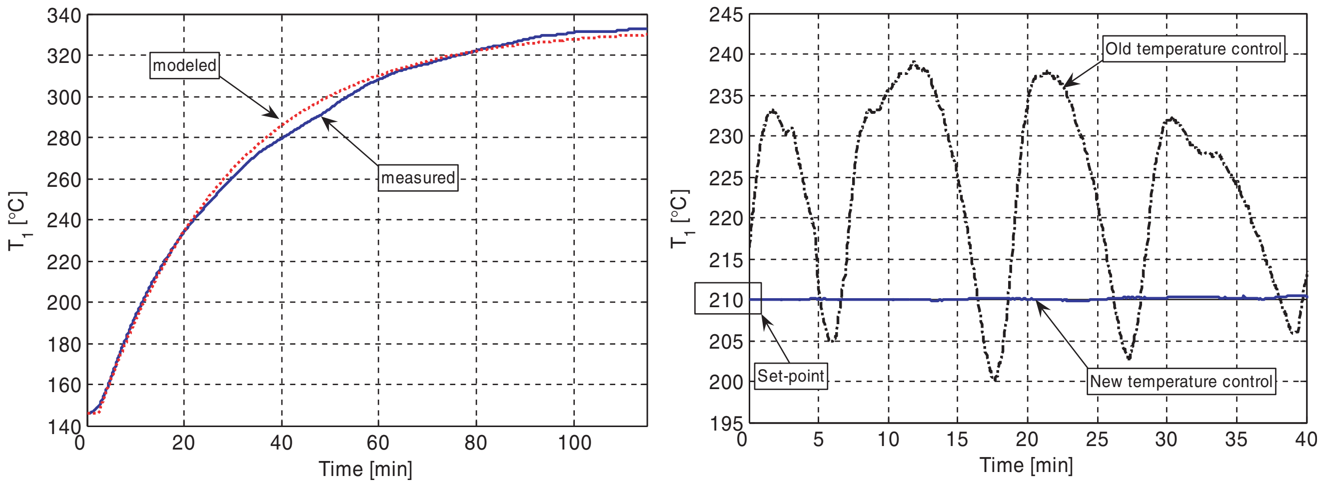


Fig. 7. Heater band 1. Left: measured and modeled step responses. Right: closed-loop performance.

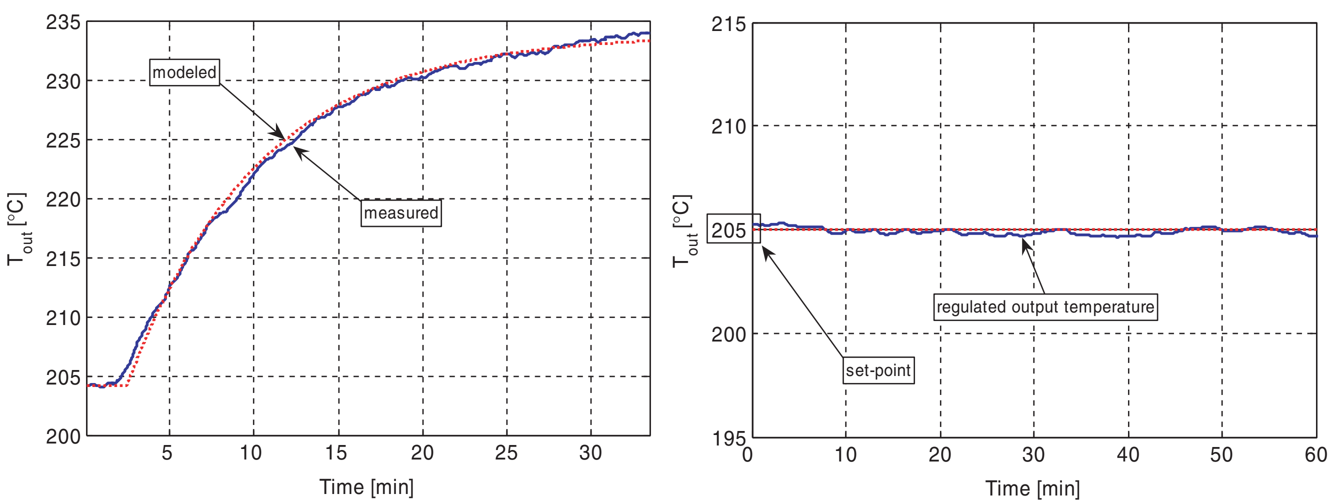


Fig. 8. Outer temperature control loop. Left: measured and modeled step responses. Right: closed-loop performance.

- The *delay* represents the polymer transport delay along the extruder. This delay is also evident by visual inspection of Fig. 8.

On the basis of (4) the PID parameters have been tuned (proportional gain $K_P = 3.9741$; integral time $T_i = 287.98$; derivative time $T_d = 72.07$). Fig. 8 shows the quality of the estimated model, and the closed-loop regulation performance.

Control of the output pressure

Also the output-pressure control scheme is constituted by a SISO PID-based control loop. The measured/controlled variable is the output pressure $P_{out}(t)$; the input (control) variable is the screw engine inverter command voltage $V(t)$; the reference signal is the desired value of the output pressure $\bar{P}_{out}(t)$. The estimated transfer function $G_P(s)$ from $V(t)$ to $P_{out}(t)$ is

$$G_P(s) = \frac{4.9}{1 + 1.2028s} \mathrm{e}^{-0.1472s}. \tag{5}$$

Eq. (5) represents the relationship between the inverter command voltage and the output pressure and its parameters has the following menaning:

- the *gain* represents the proportional relation between the applied voltage and the screw revolution speed.
- The *pole* represents the energy transfer by friction from the screw to the polymer.
- The *delay* is related to the propagation of the pressure front wave into the polymer.

On the basis of (5) the PID parameters have been tuned (proportional gain $K_P = 2.0011$; integral time

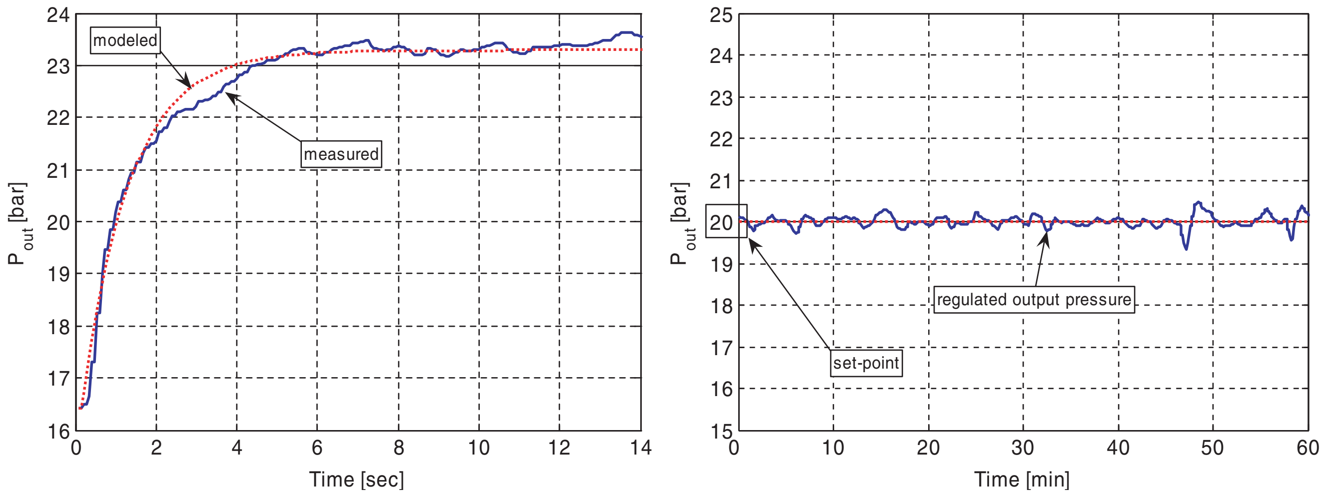


Fig. 9. Pressure control loop. Left: measured and modeled step responses. Right: closed-loop performance.

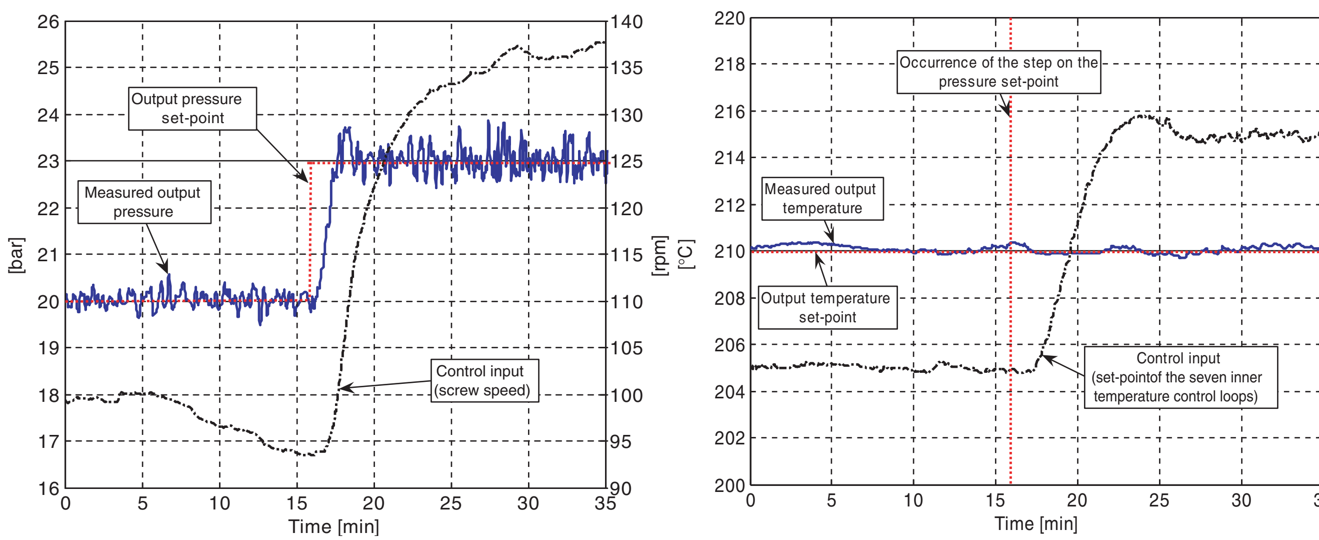


Fig. 10. Response of the output pressure (left) and of the output temperature (right) to a step in the pressure set-point.

$T_i = 0.2946$; derivative time $T_d = 0.07356$). Fig. 9 shows the quality of the estimated model, and the closed-loop regulation performance.

4. Experimental results

The whole control system described in the previous section has been extensively experimentally tested. In this section a small set of experiments is briefly illustrated and discussed. The aim of these experiments is to enlighten the main features of the designed control architecture.

Interaction between the temperature control loop and the pressure control loop.

The test described in Fig. 10 is a simple step-change in the set-point of the output pressure (from 20 to 23 bar). The responses of both P_{out} and T_{out} are depicted. Notice that the pressure loop quickly reacts to this change, and smoothly brings the output pressure at the new steady-state value. It is interesting to see that the output temperature is unaffected by the pressure change; however, notice that (in order to maintain the temperature around the set-point $\bar{T}_{out} = 210^\circ$) the temperature feedback control loop increases the value of the control variable $\bar{T}$. Henceforth, as already remarked, the two control loops are not decoupled. However, thanks to the frequency-decoupling property of the system, the two independently-designed SISO loops are able to correctly regulate the output variables P_{out} and T_{out}.

The dual test described in Fig. 11 is a step-change in the set-point of the output temperature (from 210° to 220°). The responses of both P_{out} and T_{out} are depicted. Similarly to the previous experiment, the output

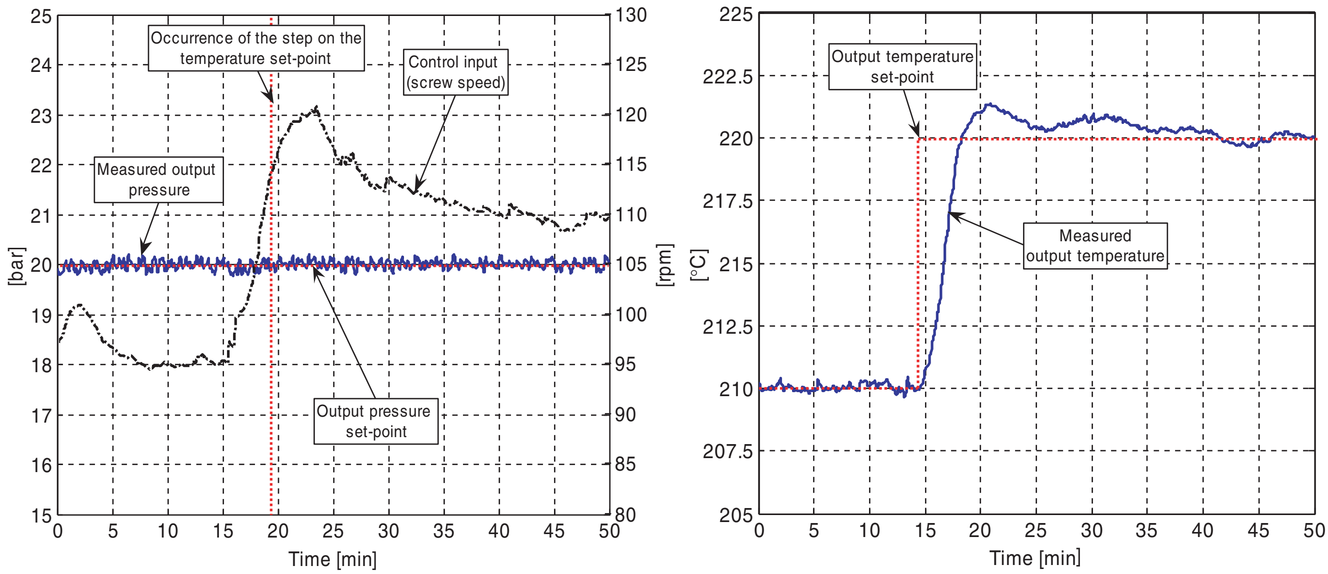


Fig. 11. Response of the output pressure (left) and of the output temperature (right) to a step in the temperature set-point.

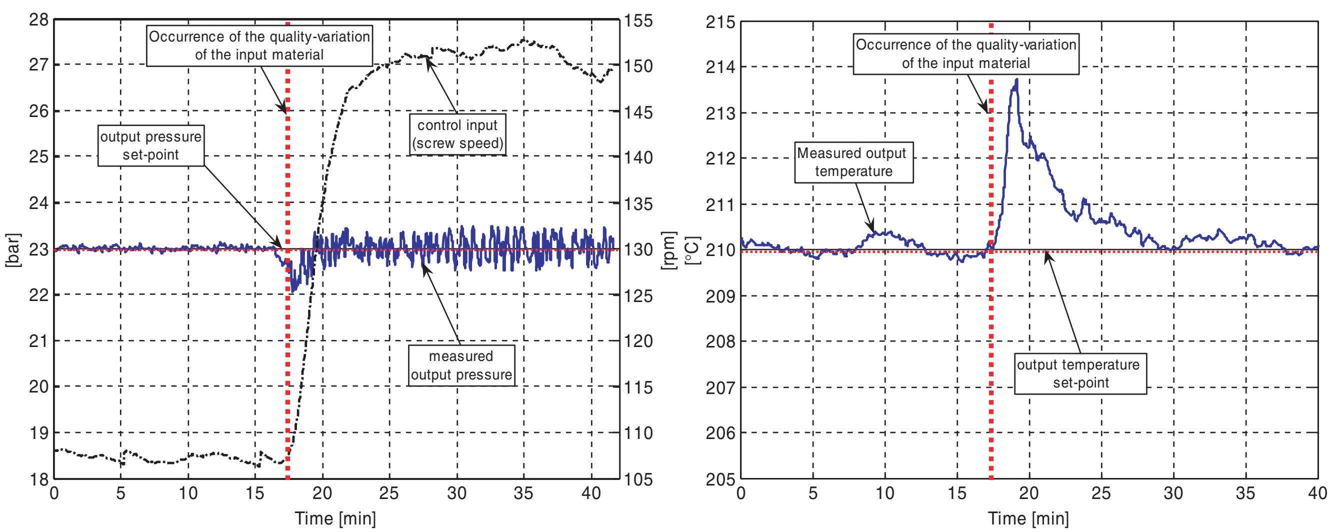


Fig. 12. Response of the output pressure (left) and of the output temperature (right) to a qulity change in the feeding material.

temperature is correctly regulated at the new set-point. The output pressure seems unaffected by the step-change; however, notice that, in order to keep P_{out} at its set-point $\bar{P}_{out} = 20\ bar$, the pressure control loops reacts to the temperature change by slightly increasing the screw speed.

Sensitivity to the quality of the input material

The second kind of experiment reported herein is a sudden change in the quality of the input material. Specifically, the feeding material is abruptly changed from high quality polypropylene (regular and uniform spheres of about 1 mm diameter) with an estimated apparent density $0.592\,g/cm^3$, to a low quality re-grinded polypropylene with an estimated apparent density $0.458\,g/cm^3$. The results of this test are illustrated in Fig. 12. Notice that the feedback control system is able to correctly regulate the output variables at the set-point values, regardless the change in the feeding material. Note that the control system quickly reacts to this disturbance and settles the temperature to 210 °C in less than 15 min and the pressure to 23 bar in less than 5 min. Notice that the higher variance of the output pressure experienced in the new condition is due to a less uniform input material and to an higher screw speed.

Sensitivity to changes in the rheological properties of the input material

The third kind of experiment reported herein is a sensitivity-test of the control system to changes of the extruded material. As a matter of fact, recall that

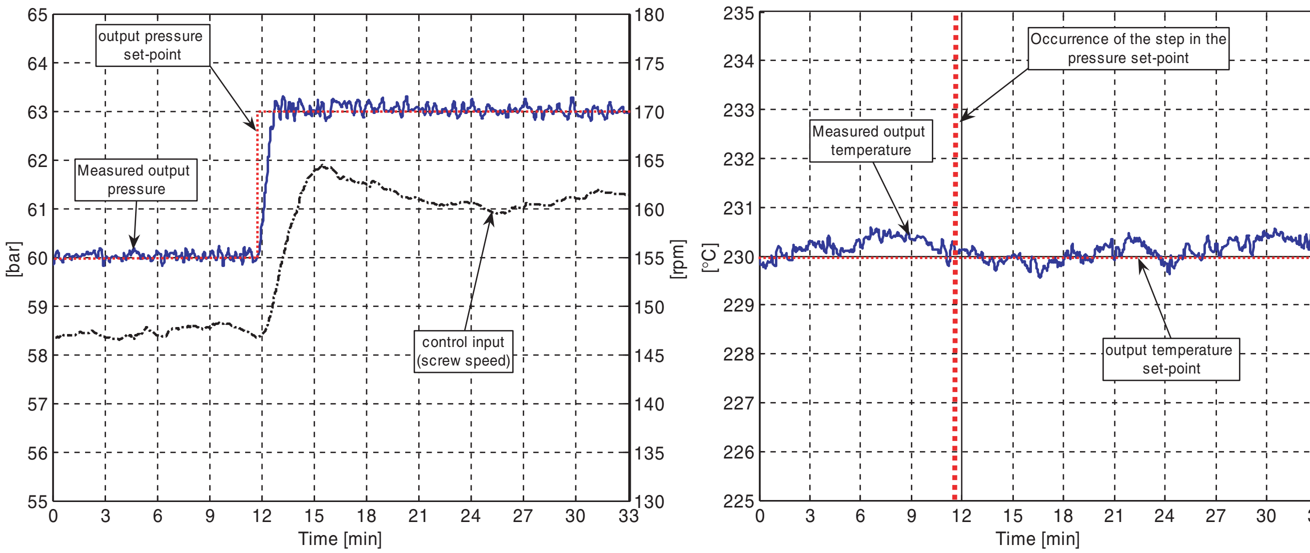


Fig. 13. Response of the output pressure (left) and of the output temperature (right) to a step in the pressure set-point, when using polyethylene instead of polypropylene.

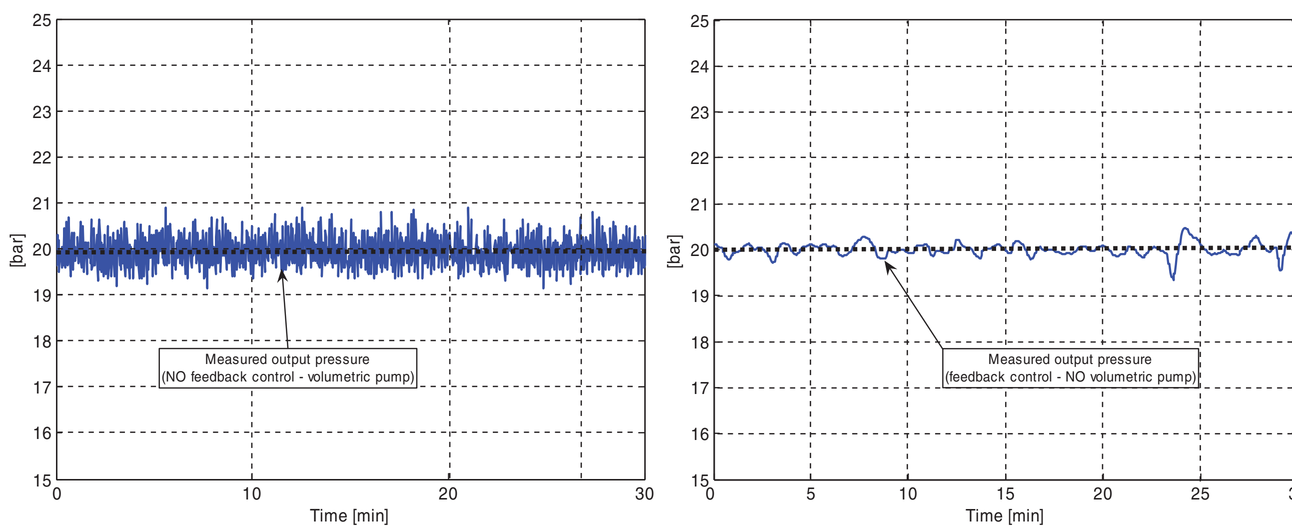


Fig. 14. Regulated output pressure. Left: SSE with a mechanical volumetric pump and no feedback control. Right: SSE with the feedback control system and no volumetric pump.

all the parameters of the control system have been tuned using polypropylene. It is interesting to see if the control system requires a re-tuning, when (e.g.) polystyrene or polyethylene are used (which have rheological parameters very different from those of polypropylene). The results of a step-response to pressure set-point when using polyethylene is displayed in Fig. 13. Note that—even the material, and the temperature/pressure set points are significantly changed from those of the previous experiments—the control system works correctly, showing high robustness properties with respect to material changes.

Comparison with a pump-equipped extruder.
As a final experiment, the behavior of the feedback-controlled extruder has been compared with the behavior of an extruder equipped with a mechanical volumetric pump (and no feedback control). As a matter of fact, it is a common practice to introduce a pump in the extrusion line to stabilize the pressure of the material at the output. The results are displayed in Fig. 14. Notice that in both configurations, the pressure is accurately regulated at the desired value. However, notice that the pressure variance is higher when the volumetric pump is used; this is due to vibrations induced by the pump.

This simple experiment shows that the feedback-control of the output pressure is a viable and cost-effective alternative to the use of a volumetric mechanical pump (the pump is an expensive component, which requires maintenance and is subject to mechanical failures). The feedback-control scheme however has several additional advantages: it is more flexible, it is less failure-prone, and it can implement more sophisticated regulations strategies (e.g. during the transients in set-point changes).

5. Conclusions and future work

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

Real-time regulation of temperature and pressure has been effectively achieved by means of a simple but effective control architecture based on two independent outer SISO loops, and seven identical inner SISO loops for local-temperature control.

The performance of the overall 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 and type of the material; the regulation achieved provides very small steady state errors both for pressure and temperature.

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