Single Screw Extruder Temperature Control Using PLC and HMI in Cable Production Process

Igor Kocić, Saša S. Nikolić, Aleksandra Milovanović, Darko Mitić, Petar Đekić and Nikola Danković

***Abstract*— In this paper it is developed and described the control software for the temperature regulation of the extruder zones with the mutual influence of zones. Extruder zone temperature control realized using Siemens PID_Temp block FB1132. PID_Temp block does not take into account the interaction of zones. This effect can only be taken into account if all zones are adjusted at the same time. The temperature process of the extruder was identified with an emphasis on the mutual influence of the zones. After that, a simulation was performed in Matlab and Simulink, and the results were experimentally verified using Siemens' LSim_LIB_V3_0_0 library and in a real process.**

***Index Terms*— Extrusion, zone temperature identification, PID Temp controller, PID tuning.**

I. Introduction

Extrusion [1, 8] of plastics and rubber is basically a continuous process. The starting raw material is usually in powder or granules, while in the case of rubber extruders it can also be in the form of a belt. The raw material moves from the basket under the action of gravity towards the feeder, and then enters the cylinder. A screw is placed in the cylinder, which transports the mass in advance under the action of the drive, the mass is further heated, homogenized and finally formed into the desired shape by passing through the tool. The machine in which this process takes place is called an extruder. Single-screw extruders have a huge application in polymer processing, they are simple constructions, have good technical performance, they are cheaper than multi-screw extruders.

Extruder temperature control is a problem that occurs very often in the industry. The main goal of temperature control is to maintain the set temperature. The extruder [1] consists of three basic units:

1. feed zone,
2. melting (compression) zone, and
3. pumping zone

In Section II we analysis the mutual influence of zones in terms of heat transfer from zone to zone on real extruder. Based on the recorded characteristics for zones 1, 2 and 3, a model of the mutual influence of the zones was made. Based on the zone influence model, the synthesis of the temperature controller was performed in Section III using the Siemens PID Temp controller and software was written in SCL for the simultaneous setting of the PID parameters of the zone controller. In chapter four, a check of the controller operation was performed using the Siemens simulation library LSim_LIB_V3_0_0.

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II. Extruder Zone Temperature Identification

Figure 1 shows a diagram of a single-screw extruder [1] with nine zones. The basic parts of each extruder are hopper, barrel, screw and head with tool. Each zone of the extruder has its own heating heater, if necessary a cooling fan and a sensor that measures the current temperature value. In addition to measuring the temperature, the melting pressure is also measured at the place where the tool is located. Zones 1 to 5 have heater and cooler, zones 6 to 9 have only heater, cooling is done by the influence of ambient temperature.

It is noticed that zones 2, 3, ..., 8 are inner zones, and zones 1 and 9 are outer zones, and therefore the character of heat dissipation is different.

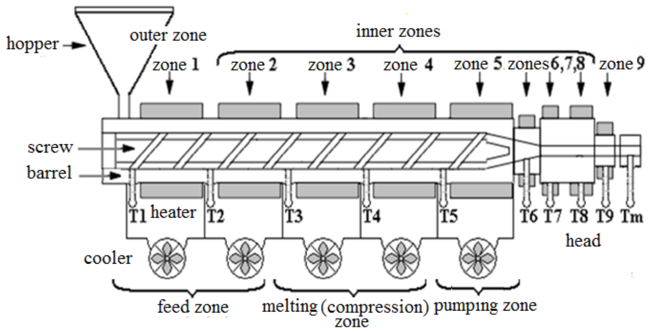

Fig. 1. Diagram of a single-screw PVC extruder

In determining the mutual influence of the zones, we started from the assumption that the control object in this case is the extruder cylinder is homogeneous and isotropic, which is correct because it is made of the same material. The influence of the heater and fan transmission function has not been considered.

In the general case, the temperature field of the extruder cylinder is non-stationary and can be described by the

 ISBN 978-86-7466-930-3

following equation [4, 8]:

$$T = f(x, y, z, t) \tag{1}$$

When heating, the temperature at the measuring points changes over time (2), for isotropic materials, Fourier's law [8] of heat conduction applies (3), where Q is the amount of heat, S is the area, dQ/dS is the specific heat flux, and λ is the heat conduction coefficient:

$$\frac{\partial T}{\partial t} \neq 0 \tag{2}$$

$$dQ = -\lambda \nabla (T) dSdt. \tag{3}$$

If we take into account that the temperature changes over time, which is the case, we get a partial differential equation of parabolic type:

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2} \tag{4}$$

For further simplification, it is assumed that the temperature at the measuring points is equal to the temperature of the entire section, the temperature of the section is considered to be the temperature of the extruder zone. In this way, we consider sections to be isothermal surfaces. For the of further simplification, we will consider that the temperature is transferred only along the x axis (x>>y, z in practice the ratio of length and diameter of the cylinder in PVC extruders is large) Fig. 2 and that it is a stationary temperature field. At the time of temperature measurement at the zone boundaries, we can consider it constant.

If we now observe the part of the cylinder between the temperature measurement points of zone 1 (T1) and zone 2 (T2) and consider that these temperatures are constants, and then the following applies to the temperature field Eqs. (4) and (5) reduces to (6) where a is thermal diffusion coefficient:

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{5}$$

$$\frac{\partial T}{\partial t} = 0 \ , \frac{\partial T}{\partial y} = 0, \frac{\partial T}{\partial y} = 0 \tag{6}$$

$$a\frac{\partial^2 T}{\partial x^2} = 0 \tag{7}$$

$$\frac{\partial T}{\partial x} = const. \tag{8}$$

By integrating (7) and taking the boundary conditions T(0)=T1, T(L)=T2, where L is the distance from the temperature measurement point T1 to T2, we get that the temperature in x coordinates changes according to (8):

$$T(x) = T_1 - \frac{T_1 - T_2}{L} x \tag{9}$$

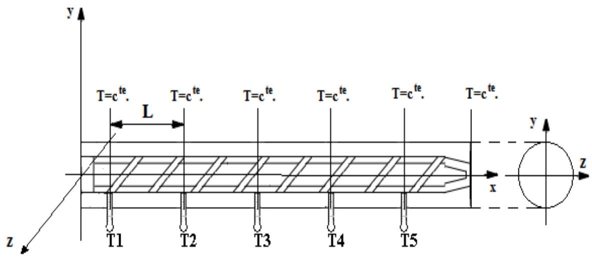

Fig. 2. Extruder cylinder (barrel) in *x, y, z* coordinate system observed along the x axis

When performing the above equation, we started from the assumption that T1>T2, that only zone 1 is heated, and zone 2 is not. In order to determine the mutual influence of the zones, measured was applied on real Royle 4 1/2" extruder during heating and cooling, heating of zone 1 was done first, where the temperatures in zones 1 and 2 were measured, zone 2 was not heated. The ambient temperature at which the experiment was performed is Ta=17°C. Fig. 3 shows the influence of zone 1 on zone 2 as well as the temperature difference between zones 1 and 2.

The extruder was then cooled to ambient temperature. Only zone 2 was heated and the characteristics of zone 2 were recorded. Then the extruder was cooled, and zones 1, 2 and 3 were heated, and the temperature characteristics of zones 1, 2 and 3 were recorded at the same time so that the mutual influence of zones could be considered. Fig. 5.a shows the characteristics of only zone 2 which is heated by itself and Fig. 5.b shows the characteristics of zones 1, 2 and 3 which are heated at the same time. The extruder is heated to a temperature of 100 ° C, which corresponds to a time of about 25 min. Ambient temperature T_a=17°C.

The Matlab software package was used to draw the temperature characteristics of the characteristic zones.

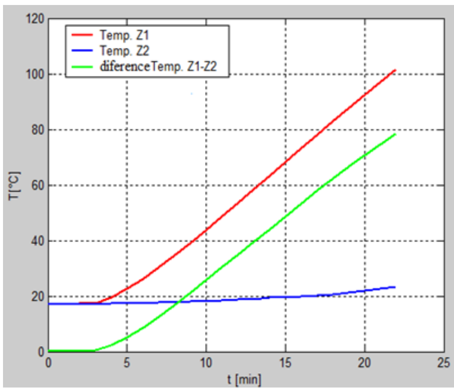

Fig. 3. Influence of Zone 1 to Zone 2

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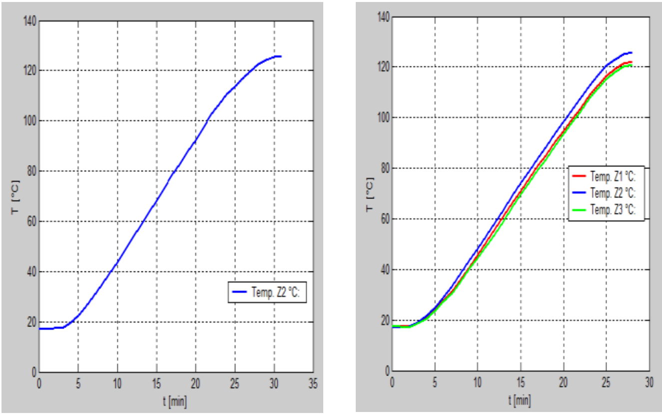

Fig. 4. Characteristics of heated

From Fig. 4 it is clearly seen that the heat transfer from zones 1 and 3 directly affects the temperature of zone 2. In Fig. 5.b we notice that the temperature of zone 1 is slightly higher than the temperature of zone 3, the reason is that zone 1 is the outer zone , and its adjacent zone is the feeder zone whose mass is less than zone 4. Zone 4 is not heated, so part of the heat from zone 3 passed to it.

In identifying and determining the process model, we started from the FOPDT model (9), which approximated the process, starting from the assumption that the transfer function of the object that controls astatism is zero. The parameters of the model are determined on the basis of the bounce response in the open coupling. The moment when the bounce trigger is brought is considered as the zero moment. Based on the recorded characteristics, the dead time T_u, the time constant T_u and the gain K were determined using the Küpfmüller method [10], so the model of the heating process for all three zones is described by the transfer function:

$$G_{ob}(s)=\frac{k_{ob}}{1+sT_{ob}}e^{-sT_u} \tag{10}$$

To determine the parameters T_u and T_{ob}, a program was written in Matlab. Table gives the values first only for zone 2 when only it is heated, and then for zones 1, 2 and 3 that are heated at the same time.

TABLE I
HEATING ZONE 2 ONLY, AND ZONE 1, 2, 3

	only zone 2 is heated	zone 1, 2, 3 are heated at the same time		
	zone 2	zone 1	zone 2	zone 3
T_u[min]	5.5882	5.05769	4.214	5.117
T_{ob}[min]	21.098	16.654	16.214	17.153
K_{ob}	0.869	0.912	0.945	0.902

Based on the measurements, it is clear that the times T_u and T_{ob} for zone 2 are higher when only zone 2 is heated. It can also be seen that when zones 1, 2, 3 are heated, that zone 2 reaches the temperature the fastest, where the impact of zone 1 and zone 3 on zone 2 is observed.

FOPDT models of zones 1, 2 and 3 were used for the initial analysis of the process. For further analysis, an attempt was made to determine the PT_2 model based on the Streitz approximation through two points [3]. The PT_2 process model is given in (11) where K are the gain of the object, and T_2 are the time constants of the PT_2 model.

$$G_{ob}(s)=\frac{k_{ob}}{(1+sT_1)(1+sT_2)} \tag{11}$$

If the analysis of the ratio T_{ob}/T_u from table I according to table II (T_{ob}/T_u<9,65) is performed, it is concluded that it is impossible to determine the characteristics of the process described by the PT_2 model according to Streitz's identification method [3]. After that, models were determined for all three zones based on the PT_N model (12), where T is the process time constant, n is the order of the PT_N model, T_{ob} is the object gain taken from the FOPDT model [3]:

$$G_{ob}(s)=\frac{k_{ob}}{(1+sT)^n} \tag{12}$$

TABLE II
RELATIONSHIP BEETWEN FOPTD AND PTN MODEL

n	1	2	3	4	5	6	7
T_{ob}/T_u		9.65	4.59	3.13	2.44	2.03	1.75
T_{ob}/T	1	2.718	3.695	4.463	5.119	5.699	6.226
T_u/T	0	0.282	0.805	1.425	2.1	2.811	3.549

Based on that, a model of the third order process is made for all three zones. To calculate the time constant of the PT_N model, a program was written in Matlab. The time constants T for the sweater zones are given in Table III.

TABLE III
VALUE OF THE TIME CONSTANT OF THE PTN MODEL

	only zone 2 is heated	zone 1,2,3 are heated at the same time		
	zone 2 (n=3)	zone 1 (n=3)	zone 2 (n=3)	zone 3 (n=3)
T [min]	5.710	4.507	4.3887	4.643

Figure 5a shows the temperature difference $T_{z2}-T_{z1}, T_{z2}-T_{z3}$ and Fig. 5b analyzes the influence of zone 1 on zone 2 according to the equation $\left(T_{z2}-T_{z1}\right)/T_{z2}$ and the influence of zone 3 on zone 2 according to the equation $\left(T_{z2}-T_{z3}\right)/T_{z2}$.

The mutual influence of the zones during the simultaneous heating of zones 1, 2 and 3 is the greatest during the transition process when it moves up to 8%, after that it decreases and moves in up to 4% Fig. 5.

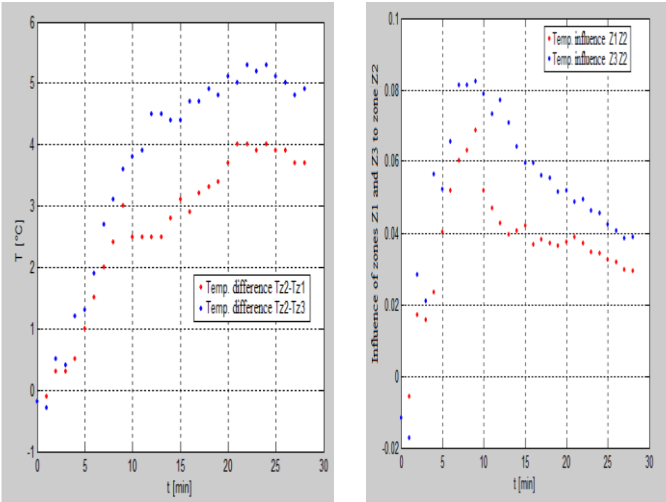

Fig. 5a. Fig. 5b.

Fig. 5. Influence of zones Z1 and Z3 on zone Z2

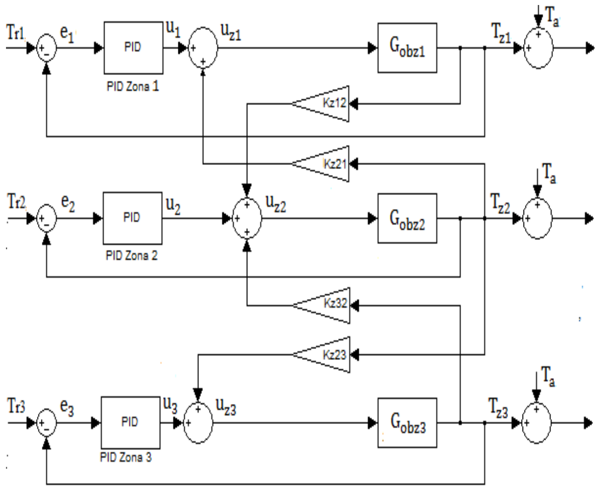

Fig. 6. Model of mutual influence of zones

It is noticed that the temperature difference between zone 2 and zone 3 is greater than between zone 2 and zone 1, the reason is that zone 1 is an external zone, and adjacent to zone 3 is zone 4 which is not heated, so part of the heat is removed from zone 3 to zone 4. Fig. 6 shows a model of the mutual influence of zones.

The equation (13) [9, 10] applies to the simulation model of the impact of zones 1 and 3 on zone 2:

$$T_{z2}(s)=G_{obz2}\left(u_2+k_{z12}T_{z1}+k_{z32}T_{z3}\right) \tag{13}$$

In general, applies equation (14), where (i = 1,…,n) is denoted by observed zone:

$$T_{zi}(s)=G_{obzi}\left(u_2+k_{z(i-1)i}T_{z(i-1)}+k_{z(i+1)i}T_{z(i+1)}\right) \tag{14}$$

When it is taken into account that zone 2 affects zones 1 and 3, can applies equation (15) [9,10] where the coefficient K_{z2z2} takes into account that part of the energy of zone 2 is spent on heating zones 1 and 3.

$$T_{z2}(s)=G_{obz2}\left(u_2+k_{z12}T_{z1}+k_{z32}T_{z3}-k_{z2z3}T_2\right) \tag{15}$$

When simulating the mutual influence of zone heating, all zones are identified separately. This means that it is necessary to heat only the observed zone, make its model, cool it and its neighboring zones. Repeat the procedure for all zones observed. In this way, the coefficient K_{z22} can be determined by comparing the influences when the heated zones are individually and all at once, so model (14) is applied for the simulation.

III. SYNTHESIS TEMPERATURE CONTROLLER

Zone temperature controler is realized using a Siemens PID_Temp block FB1132 [10] with anti windup function and adjustable weight coefficients for proportional and integral action which is a continuous PID controller designed for heating and cooling applications, where y is output of PID controller, K_p proportional gain, b weight coefficient of proportional action, w set value, x measured value, T_i time constant of integral action, T_d time constant of differential action, and time delay differential action, c weighting coefficient of differential action.

$$y=k_p\left[(bw-x)+\frac{1}{T_is}(w-x)+\frac{T_ds}{aT_ds+1}(cw-x)\right]. \tag{16}$$

The PIDT controller (Siemens PID temperature controller block) (16) is integrated within the PID_Temp block [10]. The configuration and algorithm for setting the parameters of the PID_Temp block parameters is performed using the TIA Portal, where one instance is created for each control loop. For zone i, InstPIDTemp(i) is assigned a data block specifically DB(i) within which all settings for that instance are stored. Instances are called from the OB30 block (cyclic interupt) Fig. 7 whose call time is set to 0.1s.

The PID_Temp block has two setup algorithms: pretuning and Fine Tune. For both tuning algorithms from TIA Portal software Siemens does not give a closer explanation of which criterion it uses to obtain parameters. Specifies only the necessary conditions for executing tuning algorithms.

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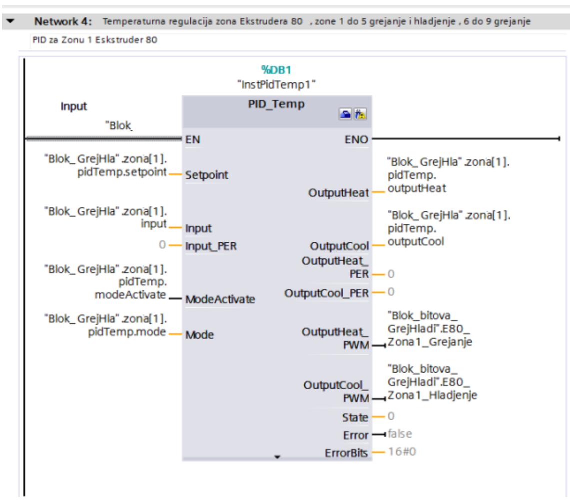

Fig. 7. Calling InstPIDTemp1 from OB30 block for zone 1

The disadvantage of individual adjustment of zones [11, 14] is reflected in the fact that the mutual influence of zones through thermal coupling is not fully taken into account. For this reason, software has been developed to simultaneously enable the setting of all zones from the HMI panel.

Before switching on the pre-tuning, the temperatures of the operating points of all zones are set, which must be higher than the current temperature, it is best to start from the ambient temperature. The inactive PID mode is selected for all zones. When performing pre-tuning, the heating pre-tuning is performed first, the cooling of the zones is temporarily switched off so that one of the zones does not adjust the heating parameters and its adjacent zones have completed the adjustment and switched to cooling mode. This creates a false temperature coupling. When the setting of the heating parameters is completed, the setting of the cooling parameters for all zones is switched on.

IV. Experimental Results

Experimental results were obtained using Royle 4_1/2" extruder for PVC insulation and Siemens library LSim_LIB_V3_0_0 [15], Siemens PLC type S7 1500 3PN/DP, HMI 1500 Comfort series. The simulation of the interaction of zones 1, 2 and 3 was implemented in the software using the model of the interaction of zones by (14), Fig. 8.

The zone transfer functions are simulated by the Siemens function to simulate the third-order process LSIM_PT3. Simulation software was written in SCL. Part of the Zone 2 simulation software is shown in Fig. 8.

The transfer function (12) was realized using the LSim_PT3 block. At the input of the block Block_Zone2 are the control signals from the PID block (InstPidTemp2) of zone 2 and the coefficients of mutual influence of the zones. In the function block Block_Zone2, a program is written that realizes the equation of influence of zone 1, 3 on zone 2 (13). The value thus obtained is fed to the input of the block LSim_PT3_Zone 2, at the output of which the value for the temperature of zone 2 is obtained.

In the theoretical part, only heating is considered, and here the results for heating and cooling are given, Table IV. The simulation program is called from the OB30 object block with a selection period of 0.1 s. In Fig. 9 shows the response ratio of the calculated PID controller according to the PT_3 model and the controller obtained using the PLC simulation library for zone 1. The time to reach the desired temperature of the extruder zones is completely satisfactory. given the mass of the extruder cylinder.

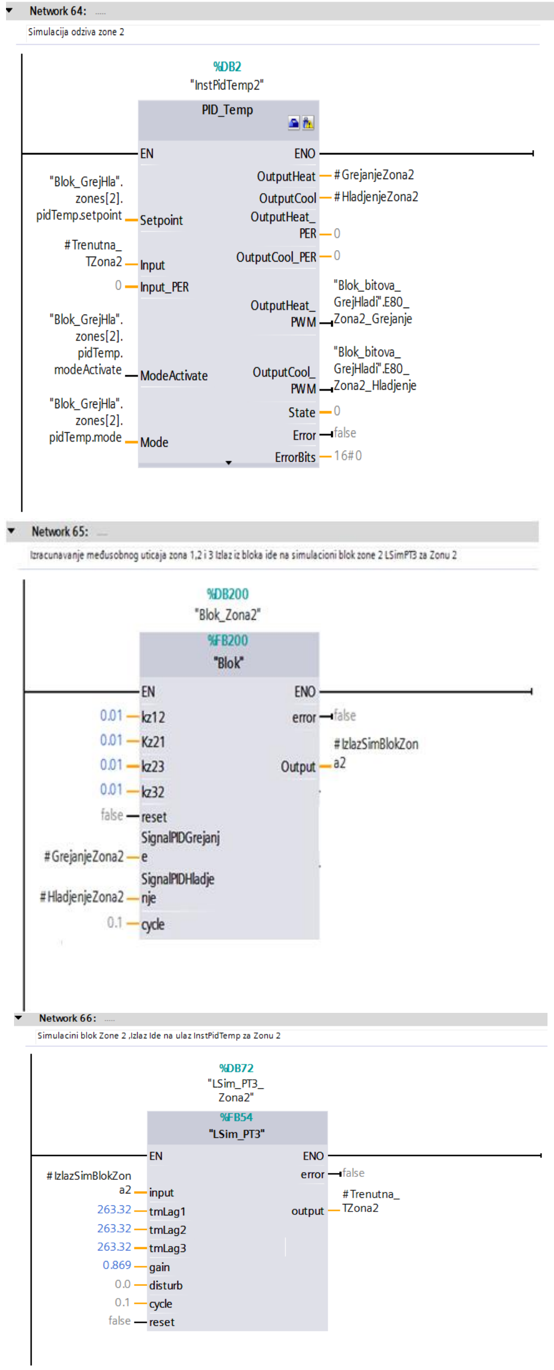

Fig. 8. Part of software for simulation of zone 2

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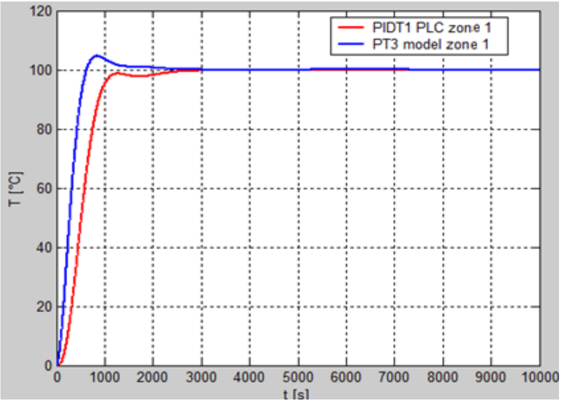

Fig. 9. Response characteristics of the calculated PID controller for PT_3 model and PIDT1 for Zone1 obtained by simulation using a PLC controller and a simulation library

TABLE IV
PID HEATING AND COOLING PARAMETERS OBTAINED USING SIMULATION ON PLC

	PID heating parameters		
	Zone 1	Zone 2	Zone 3
Kr	2.2338	2.1643	2.2562
Ti	816.98	756.866	875.896
Td	163.5282	158.118	167.8306
a	0.1	0.1	0.1
b	0.8	0.8	0.8
c	0	0	0
	PID cooling parameters		
	Zone 1	Zone 2	Zone 3
Kr	5.7454	5.7056	5.7557
Ti	317.126	273.652	359.381
Td	118.5414	114.6287	122.3443
a	0.1	0.1	0.1
b	0.8	0.8	0.8
c	0	0	0

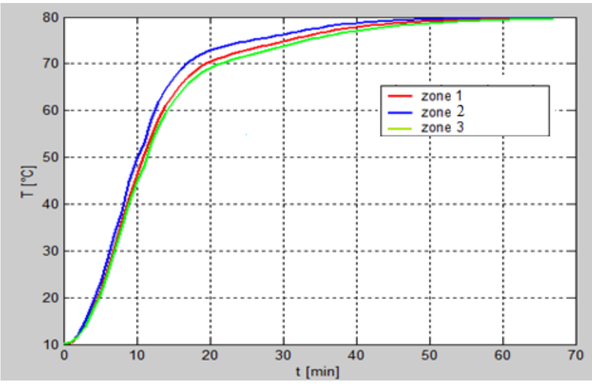

Fig. 10. Response characteristics zones 1, 2, 3 using simulation library

Figure 10 shows the real characteristics obtained by drawing in Matlab, based on the data collected by recording the temperatures of all three zones by entering in the DB block of the PLC during the simulation using the PT_3 SIM library.

V. CONCLUSION

This paper presents zone temperature controler of extruder zones with special reference to the mutual influence of extruder zones. A model of mutual influence of zones is given, a simulation is done in TIA Portal.

It has been shown that the mutual influence of the zones during the simultaneous heating of the zones is greatest during the transition process when it moves up to 8%, after that it decreases and moves up to 4%.

The paper develops software for simultaneous adjustment of parameters of all extruder zones, as well as for adjustment of individual zones. The big advantage is that the software enables the adjustment of extruder zones from the HMI panel and not only from the TIA Portal software package.

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ISBN 978-86-7466-930-3