Temperature profile in the extruder barrel matters

Abstract

Too low or too high extruder barrel temperatures cannot be used in production. However, the best barrel temperatures are almost never determined with objective criteria. Temperatures influence the throughput of the extruder besides the melt temperature and several other consequences of extrusion. These relations are fairly complicated, and it is not efficient to determine good temperature profiles simply by trial and error experimentation. Higher throughputs are often limited by limits on the melt temperature.

Systematic experiments followed by development of nonlinear models result in the necessary quantitative knowledge for determining the optimal temperature profiles in a given extruder. This article describes how nonlinear models developed from a limited series of experiments can be used to calculate the best temperature profiles in presence of constraints on melt temperature. The case described in the article is of extrusion of medium voltage power cable insulations of one grade of LDPE compounded with carbon black, from one NXW80-20D extruder of Maillefer Extrusion. The approach proposed in the article was found to be efficient.

Introduction

Extruders are usually operated with barrel temperature profiles fixed after very little trial and error experimentation which leads to acceptable results. The best barrel temperatures are almost never determined with objective criteria. However, there can be a big difference between a good and a bad temperature profile. Temperatures of the barrel, crosshead and the screw affect the throughput of the extruder and several other consequences of extrusion, including the melt temperature. This article makes a point: the temperatures matter, and it is worthwhile determining their optimal values.

Nonlinear modeling

Articles [1, 2] have explained nonlinear modeling in some detail, and why it is more effective than linear statistical techniques or physical modeling. The articles also describe in short how it has been utilised for process development in several different industrial sectors. One article [3] describes in general how nonlinear modeling helps improve the efficiency of production processes in the plastics industry. This article, therefore, does not repeat these basics.

For extrusion processes, physical models can barely predict temperature and flow profiles. The materials to be extruded are usually non-Newtonian fluids. Their viscosities at different shear rates at different temperatures are usually not known well. The geometry of the screw, the extruder barrel and the crosshead are not easy to describe. The voidage in the feed zone of the extruder cannot be calculated easily. All this makes physical modeling of an extruder prone to low reliability. Empirical modeling does not have significant drawbacks if nonlinearities are taken into account. It is fairly easy and inexpensive to carry out experiments and measure all the variables of interest.

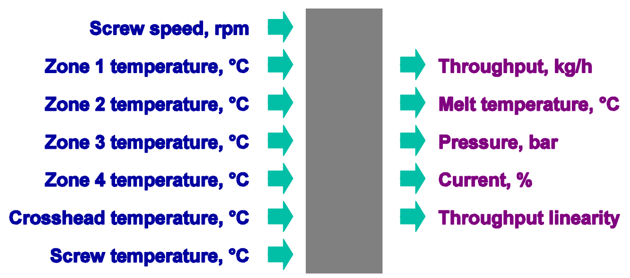

Figure 1. Variables taken into account

Figure 1 shows the variables which were taken into account for one grade of LDPE compounded with carbon black extruded from a NXW80-20D extruder of Maillefer Extrusion. The variables on the left are the input variables. The variables on the right are the consequences of extrusion which depend on the input variables.

Experimentation

A total of 31 experiments were carried out with one LDPE material compounded with carbon black. All the variables shown in Figure 1 except throughput linearity were measured. Throughput linearity was calculated as *(2F(5)-F(10))/25*, where *F(5)*, *F(10)* are throughputs at screw speeds of 5 rpm and 10 rpm respectively, as was first proposed in an article last year [4]. This number is usually positive, but in many situations, negative values have also been encountered. Throughput linearity is of importance from the point of view of ramp up, and is influenced by the temperatures to a good extent.

The effects of some of the input variables were clearly visible from the experimental data. Contrary to the common belief, the feed zone temperature did not have a significant effect on the throughput for this material (Figure 2). The second zone temperature had a fairly large effect on the throughput (Figure 3). Screw temperature also has an equally significant effect on throughput (Figure 4). All the temperatures affect the melt temperature. Figure 5 shows the effect of crosshead temperature on the melt temperature.

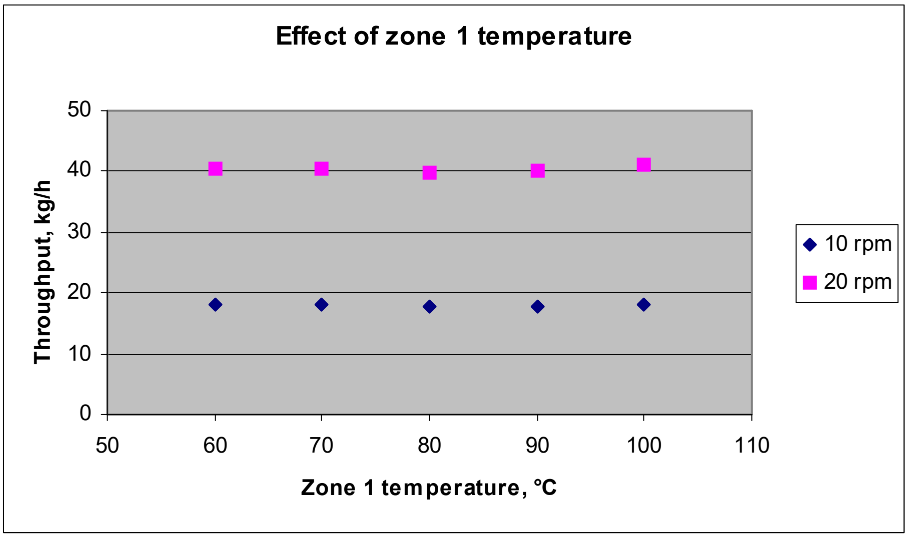

Figure 2. Effect of zone 1 temperature on the throughput

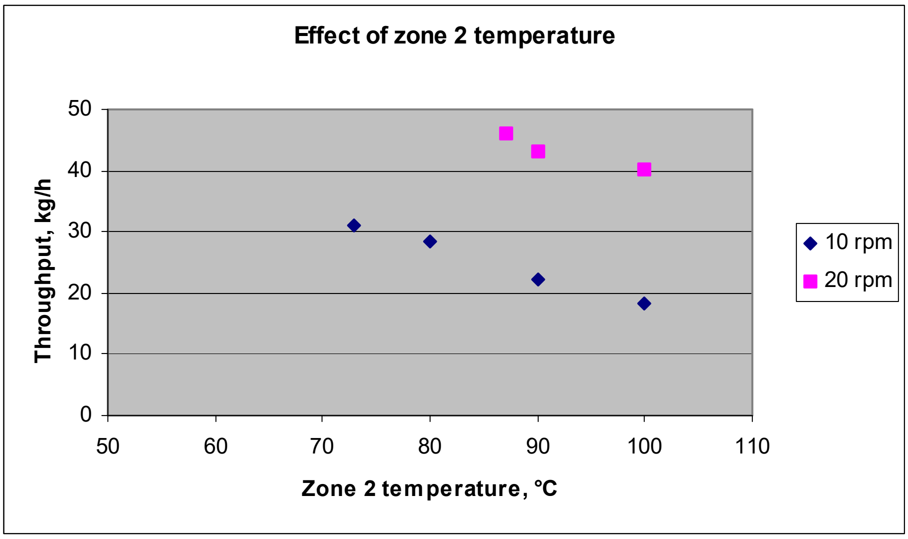

Figure 3. Effect of zone 2 temperature on the throughput

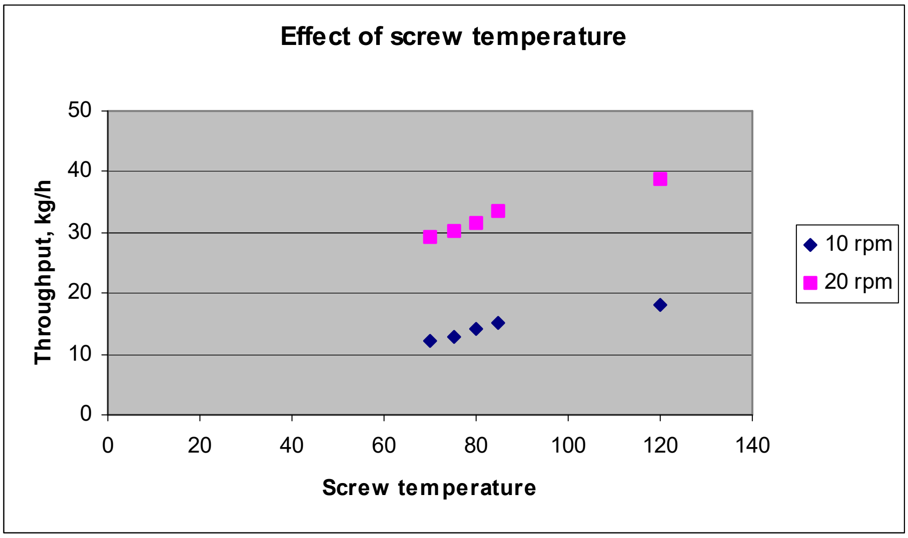

Figure 4. Effect of screw temperature on the throughput

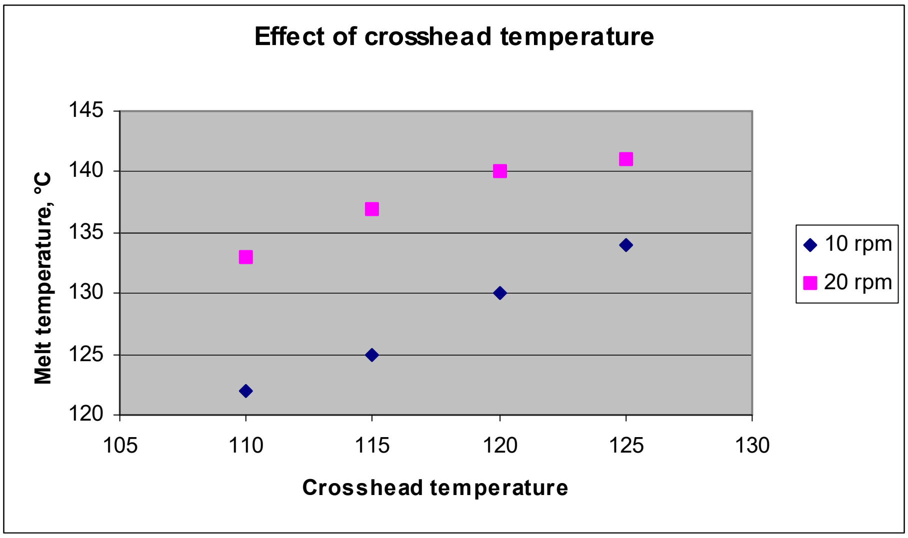

Figure 5. Effect of crosshead temperature on the melt temperature

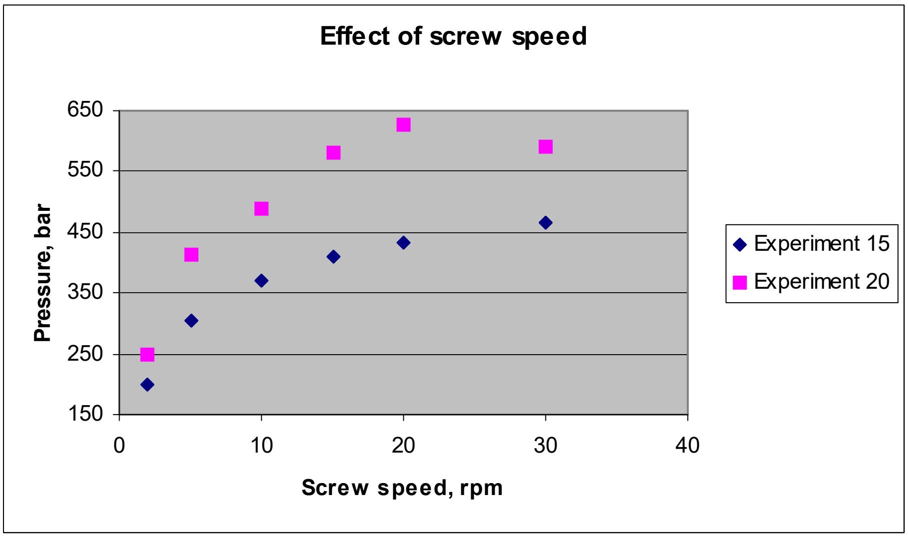

Figure 6. Effect of screw speed on pressure

Figure 6 shows the effect of screw speed on pressure. At higher screw speeds, the melt temperature can increase to such an extent that the net effect of increasing screw speed on pressure is negative. Different LDPE materials, however, behave very differently as was observed in a similar series of experiments on material supplied by another producer.

Results

Nonlinear models in the form of feed-forward neural networks were developed for throughput, melt temperature, pressure and current from the experimental data. The quality of all these four models is very good. The prediction error statistics is shown in Table 1. Throughput linearity is calculated from throughput at 5 rpm and 10 rpm. Figure 7 shows a comparison of measured values with the values predicted by the nonlinear model for throughput.

Table 1. Statistics of the prediction errors of the nonlinear models

	Throughput	Melt temperature	pressure	current
rms error	1.028	1.389	13.341	1.797
mean |error|	0.816	1.031	10.682	1.541
rms % error	5.91	1.04	3.60	4.22
max |error|	2.625	3.847	38.387	3.755
correlation	0.9953	0.9293	0.9788	0.9777

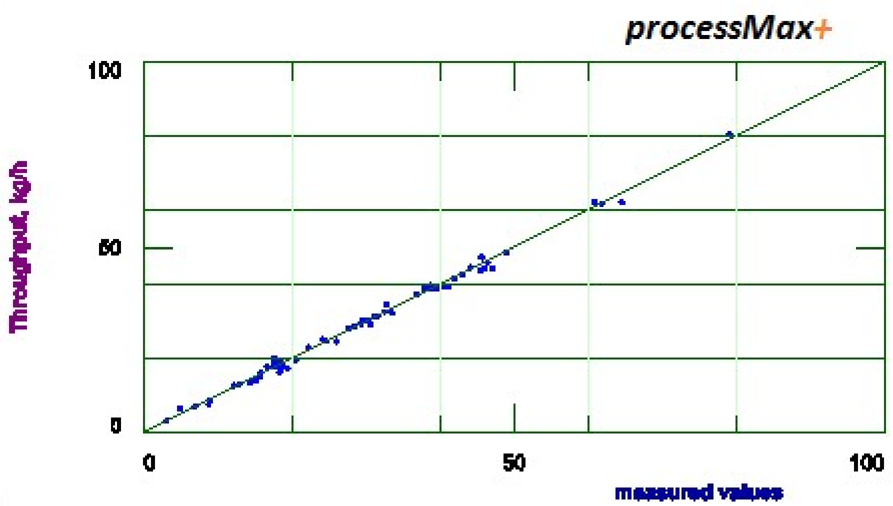

Figure 7. A comparison of measured and predicted values of throughput

The nonlinear models show the effects of input variables as are expected. Figure 8 shows the effect of screw speed on throughput with different zone 2 temperatures. Lower zone 2 temperature results in a higher throughput as well as a better throughput linearity. Figure 10 shows the small effect of screw speed on melt temperature as predicted by the nonlinear model for different zone 2 temperatures. Figure 9 shows the effect of screw speed on throughput for different crosshead temperatures. Higher crosshead temperatures lead to higher throughputs, but also much higher melt temperatures, as can be seen from Figure 11.

Figure 12 shows a complicated effect of screw speed on melt temperature for different screw temperatures. Lower screw temperatures cause less heating to the melt, but high screw temperatures result in extrudate slipping over the screw with poorer contact with the screw, resulting in a lower heat transfer as well as a lower effective screw speed. Figure 13 shows the effect of screw speed on pressure for different zone 4 temperatures. There is a maximum in the curve as was seen from the experimental data (Figure 6). Figure 14 shows the effect of zone 1 temperature on throughput linearity for different screw temperatures. From the point of view of linearity, higher screw temperatures are favourable.

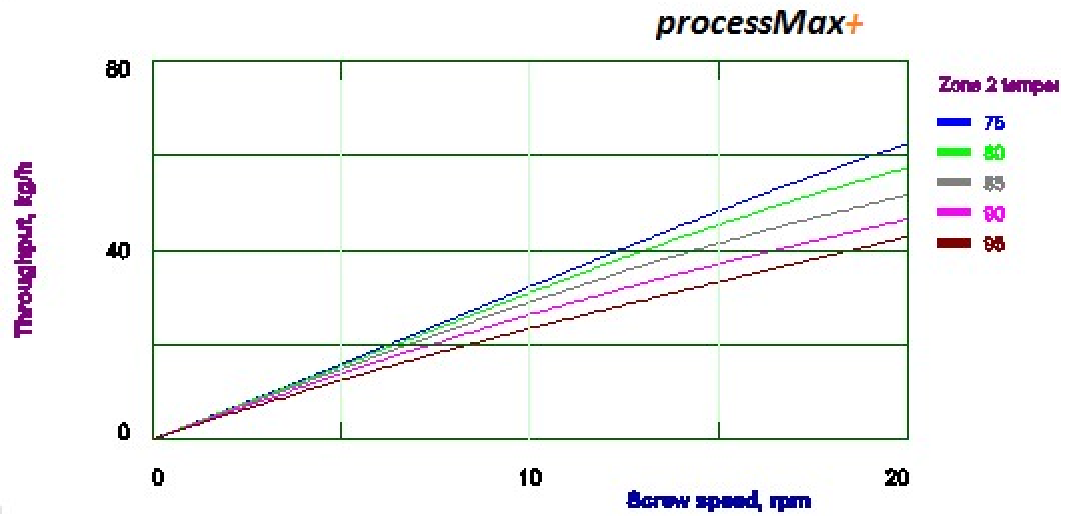

Figure 8. Effect of screw speed on throughput as predicted by the nonlinear model for different zone 2 temperatures

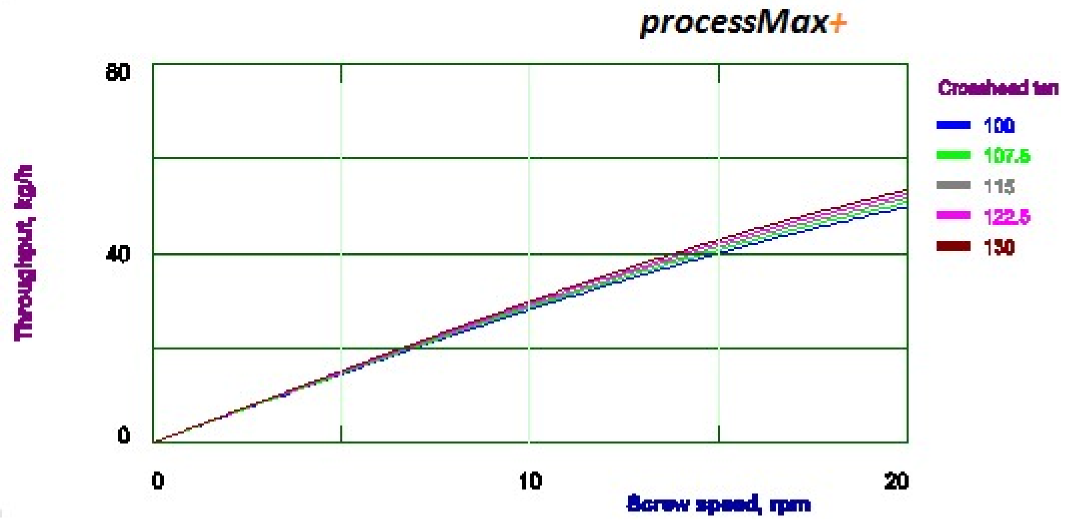

Figure 9. Effect of screw speed on throughput as predicted by the nonlinear model for different crosshead temperatures

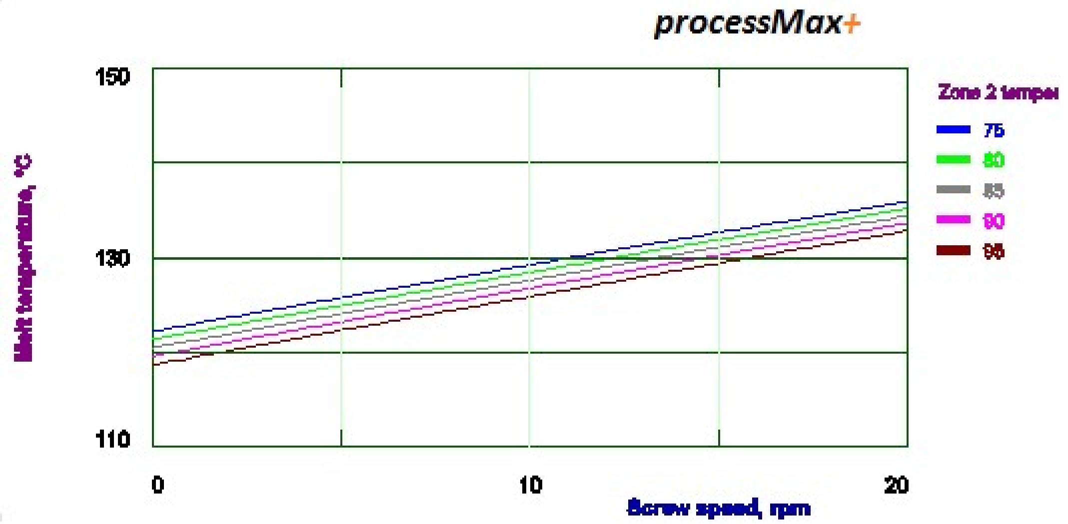

Figure 10. Effect of screw speed on melt temperature as predicted by the nonlinear model for different zone 2 temperatures

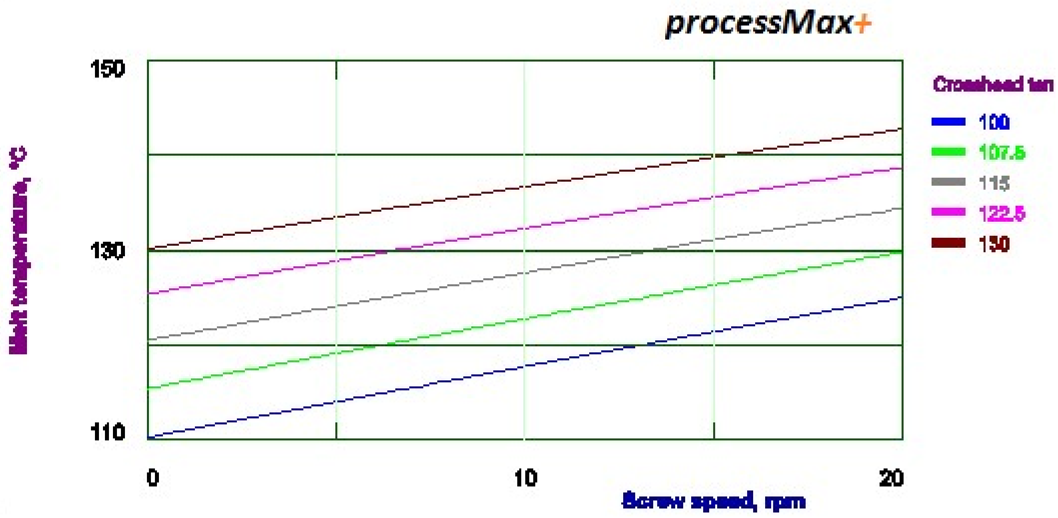

Figure 11. Effect of screw speed on melt temperature as predicted by the nonlinear model for different crosshead temperatures

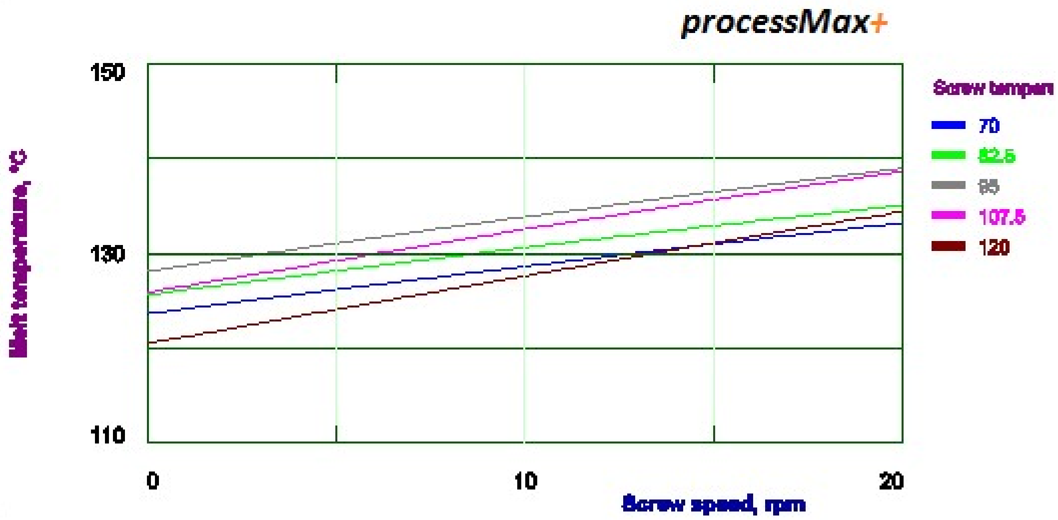

Figure 12. Effect of screw speed on melt temperature as predicted by the nonlinear model for different screw temperatures

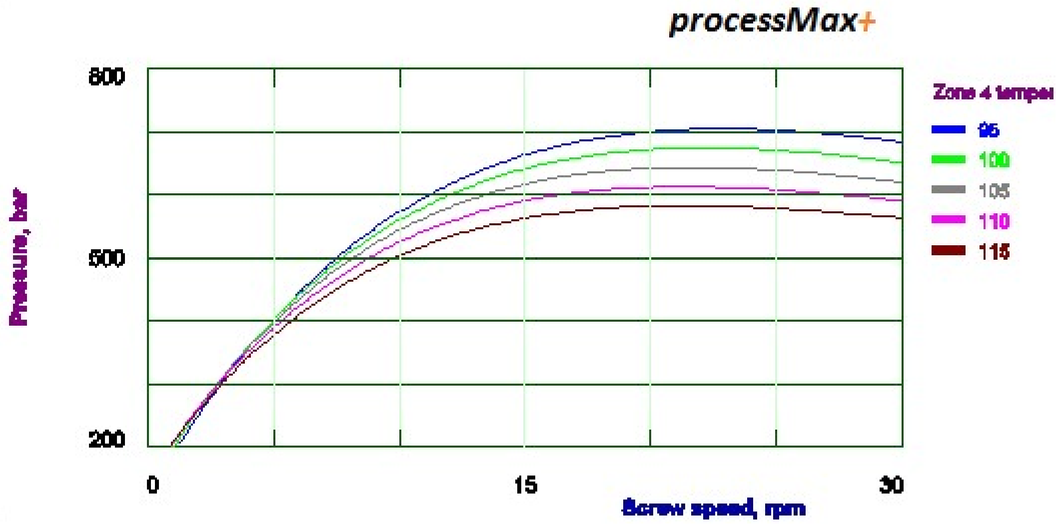

Figure 13. Effect of screw speed on pressure as predicted by the nonlinear model for different zone 4 temperatures

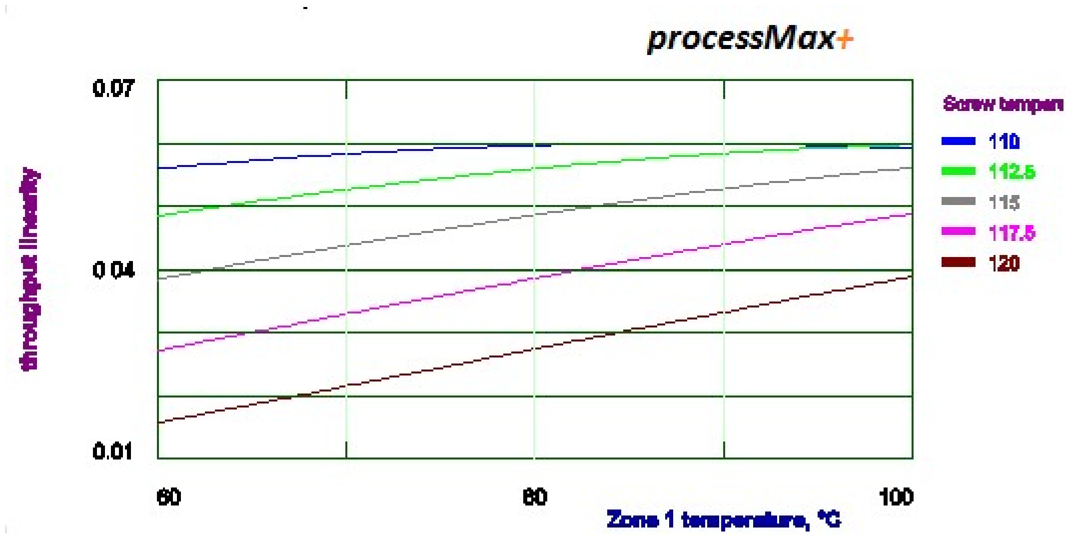

Figure 14. Effect of zone 1 temperature on throughput linearity as predicted by the nonlinear model for different screw temperatures

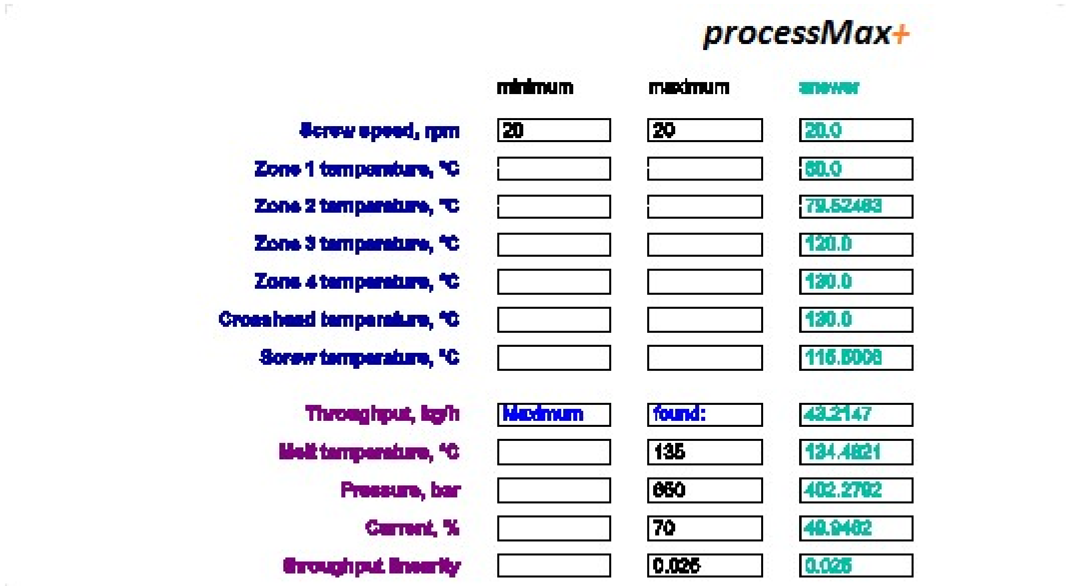

Figure 15. Calculation of an optimal set of temperatures

One of the main benefits of developing nonlinear models of processes is the possibility of determining the best operating conditions. In this case, a good operating condition is one which satisfies all the constraints on all the variables, since no variable should be too high or too low. It would be still better to find the maximum throughput in presence of constraints.

Such a calculation is shown in Figure 15. Melt temperature is restricted to below 135 °C, pressure to below 650 bar, current below 70%, and throughput linearity to below 0.025 kg/h/rpm^2. The only screw speed considered is 20 rpm. All the temperatures also have upper and lower limits. In addition, each zone temperature should be higher than the previous zone temperature. The highest throughput obtainable with these contraints on melt temperature, pressure, current and throughput linearity was found to be about 43.2 kg/h. With a highly unfavourable temperature profile, the throughput with the same constraints can be as low as 28.7 kg/h.

Conclusions

One can derive a higher throughput by tuning the temperatures of the barrel, crosshead and the screw better. The optimal conditions vary from material to material and from extruder to extruder. Too low temperatures lead to too high pressures and lower throughputs. Too high temperatures lead to unacceptable melt temperatures or slippage between the screw and the extrudate.

Nonlinear modeling from systematic experimental data is an efficient way of determining the relations between the process variables and the consequences of extrusion, as described in this article. With appropriate mathematical tools like the PROCESSMAX+ system, it becomes easy to use the nonlinear models to calculate the optimal conditions. The difference between an unfavourable set of temperatures and optimised temperatures could be as much as 50% in terms of throughput.