AN APPLICATION OF INTEGRATED DESIGN NOTATION: EXTRUDER MODELING AND CONTROL

Ina Taralova, John Edmunds,
Steven Schooling, Jim Hughes*

Control Systems Centre, UMIST, p.o. box 88, Manchester M60 1QD, UK
** BICC General UK Cables Limited, Wrexham LL13 9PH, UK*

Abstract: This work falls within the frame of the research project "Process Control System Integration" (PCSI) which aims to provide automated translation of the languages for plant modelling and simulation, such as Matlab, Simulink, State flow and IEC, in the frame of an object-based infrastructure, the Integrated Design Notation (IDN). The output of the IDN is to be Java code that runs in real time on the plant. The targeted application for the PCSI project used as a case tool is the control of extrusion process, and this paper discusses the modelling and control of a typical 90 mm plastic extruder.

Keywords: Extrusion Modelling, Structure Identification, Parameter identification, Extruder Control, Multivariable Control, Robust Control, IDN, Code Generation

1. INTRODUCTION

Process control hardware and software involve many different strategies and disciplines, such as control engineering, computer science, process and plant engineering. This type of multidiscipline inevitably leads to different styles of programming, programming techniques, languages and methods, which makes the interaction and integration difficult, and the implementation becomes complex.

The research project "Process Control System Integration" (PCSI), within which fits the current work, aims at providing solutions to the above problems. Starting with languages for plant modelling and simulation, such as Matlab, Simulink, State flow and IEC, automated translation of the previous is provided in the frame of an object-based infrastructure, the Integrated Design Notation (IDN), running under Windows NT. The advantage of IDN is that it supports the integration of control engineering expertise with design constraints, imposed by the underlying hardware architecture. The output of the IDN is to be Java code that runs in real time on the plant (see Fig.1). The targeted application for the PCSI project used as a case tool is the control of extrusion process, and this paper deals in particular with the modelling and control of a typical extruder.

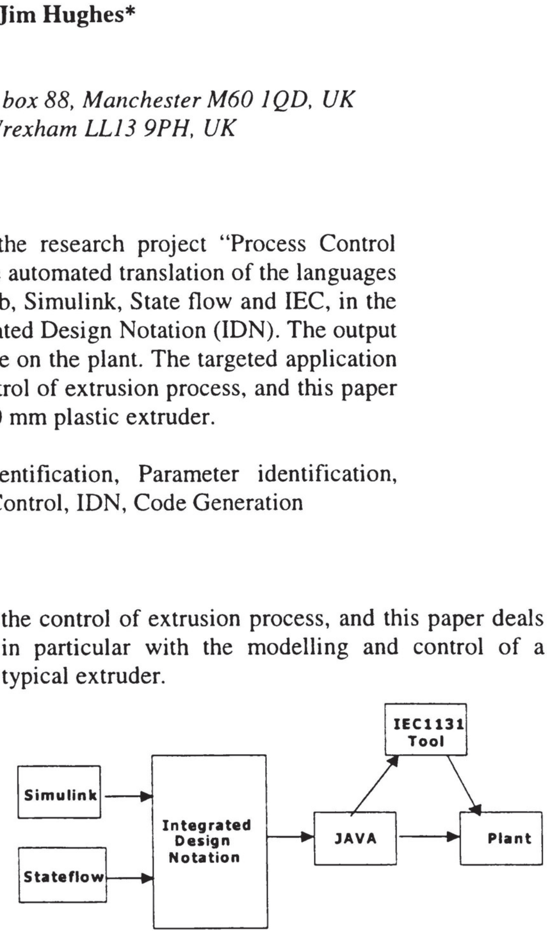

Fig.1 Schematic overview of integrated design notation.

2. DESCRIPTION OF THE PROCESS

Polymer processing (Fig.2) is very widely used in profile, sheet, foil and pipe extrusion processes, in film and bottle blowing processes and in injection moulding (McCrum and Buckley, 1997; Keith and O'Brien, 1992) The processing is a combined procedure of melt-producing, shaping and heat treatment process.

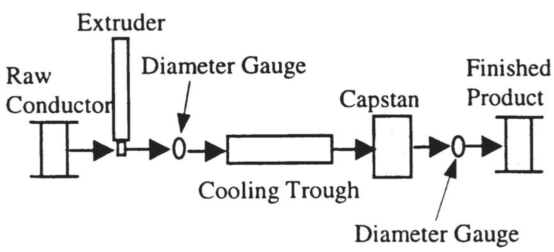

Fig. 2 Overview of the cable extrusion process

One of the most important entities of melt production is the extruder (Fig.3).

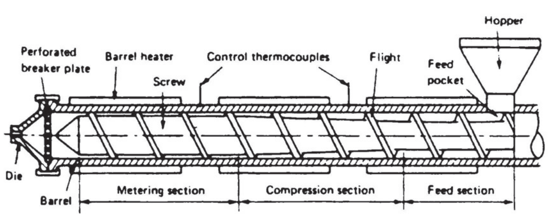

Fig. 3 Illustration of the extruder

The function of the extruder is to convert solid feedstock into a homogeneous melt and to pump it through a die at a uniform rate. Following the die, a train of equipment handles the molten extrudate in order to ensure that it cools to precisely the right shape and with the required molecular orientation.
The rotating screw takes the material – which is usually in the form of free flowing cold chips, powders or cubes – from the feed opening, through the heated barrel zones, and compacts it against the breaker plate or other restriction, so that a pressure is built up. During this period the material is forced into intimate and substantially sliding contact with the hot barrel walls and is also sheared and worked so that frictional effects are produced. The combined effects of the hot barrel walls and the heat due to internal friction in the material cause the thermoplastic to soften so that it may be forced through the restriction to the extrusion die, where it is given the required form.
The size of the extruder is defined by its internal diameter, which is normally in the range 2.5 to 15 cm. The feed from the hopper (see Fig. 3) is by gravity: the screw continuously extracts the resin it can handle from the hopper. Barrel temperatures are controlled by electrical heaters monitored by thermocouples. In the barrel, holes for the thermocouples are drilled through the steel of the barrel to just outside the wear-resistant layer, close to the melting polymer. The temperature of the die is also controlled by a thermocouple. The working of the plastic by the screw generates additional heat which can be of such magnitude, for example, to permit extrusion to continue even if the power of the heaters is switched off. Because of the heat produced by mechanical working, most extruders today are equipped with a barrel cooling system: the barrel must be provided with means both to add and extract heat.
Although numerous solutions have been elaborated to model the behaviour of the melt flow in the different sections of the extruder (rheological properties, non-Newtonian fluids approach etc), there is still lack of dynamical models suitable for control purposes and prediction (Halasz, 1993; Smith, 1999). This paper deals with this gap, and proposes a (macro) model of an extruder for the purpose of multivariable control development. The novelty of our work consists in the new approach to modelling, as well as in the realisation of the distributed control structure for the model.

3. EXPERIMENTS AND EXTRUDER MODELLING

For this particular study, a 90mm extruder is analyzed and modeled. The 90mm extruder was chosen for the trials because it was well instrumented compared to typical production extruders (especially the ability to monitor pressure along the barrel). This type of extruder has seven temperature-controlled zones. The seven barrel zones are a consequence of the extruder design – the extruder has a relatively high length/internal diameter ratio of 30 (L/D barrel length/barrel internal diameter). Therefore this type of extruder offers enough measurements necessary for the model design and identification.
These seven zones correspond to seven different temperature set points, guaranteeing given physical properties of the molten polymer in the different sections. Besides the temperature measurements, for our model development we disposed of pressure measurements, mass flow measurements, and screw speed measurements. Moreover, in order to identify the time delays between the different zones, additional measurements of the mass flow rate have been performed for different screw speeds.
In order to design the model, experiments with empty extruder (with no polymer inside) and normal regime of functioning (with polymer) have been carried out. The set points of the different zones have been set to their nominal operating values for the processed polymer. We have limited the scope of the experiment, by using only one compound, and one type of screw design.

For developing the model we use the generic idea of our system as being an energy manipulator which interacts with inputs and outputs via energy ports. In this energetic interpretation of the system behavior, the storage of information is synonymous with storage of energy, where the simplest form of storage is time integration. The analogy with electrical elements is used to model the energy storage devices, the energy dissipaters and the energy sources. Using these considerations, each of the seven zones of the extruder can be modeled as an electrical circuit. Taking into account the heat balance for each zone of the extruder, we obtain the following equation:

$$C_1\frac{dT_{1i}}{dt}+C_2\frac{dT_{2i}}{dt}+C_3\frac{dT_{3i}}{dt}+C_4\frac{dT_{4i}}{dt}+C_5\frac{dT_{5i}}{dt}= \\ =H_i-Q_i+M_i+(T_{pi-1}-T_{pi}).w_i \quad (1)$$

where w_i denotes the thermal capacity of one second worth of plastic, M_i and H_i are the energies from the motor and the heater, and Q_i is the heat loss through the heat sink. The coefficients C_1, C_2, C_3, C_4 and C_5 represent the thermal capacitances of the heat sink, heater, barrel, polymer and core respectively. If we denote

$$W_i=(T_{pi-1}-T_{pi}).w_i \quad (2)$$

and take equation (1) into consideration, then the following electrical scheme can be drawn for each of the zones (Fig. 5). The heat generation by movement M_i was split into two components, one proportional to the speed representing friction, and another proportional to viscosity*speed^2, representing sheer of the plastic with laminar flow. The viscosity was represented by an equation $k_i e^{\gamma/T4}$ where γ was 14700 and k_i was combined with the proportional constant for each zone.

Fig.5 provides better understanding of the model structure of each subsystem. It can be seen that each zone consists of five states, and its parameters reflect the thermoresistances (R) and thermocapacitances (C) corresponding to the different parts of a transversal section of the extruder: the heat sink, the heater, the barrel, the polymer and the screw.

The model is structurally identical for each of the zones. Different values were used for R_4, R_5 and R_6 when the screw was stationary and moving. The analysis of the set of data with polymer showed that different kind of disturbances influence the extrusion, like the additional energy generated by the screw, the unpredictable screw speed changes, the pressure fluctuations, the quality of material etc.

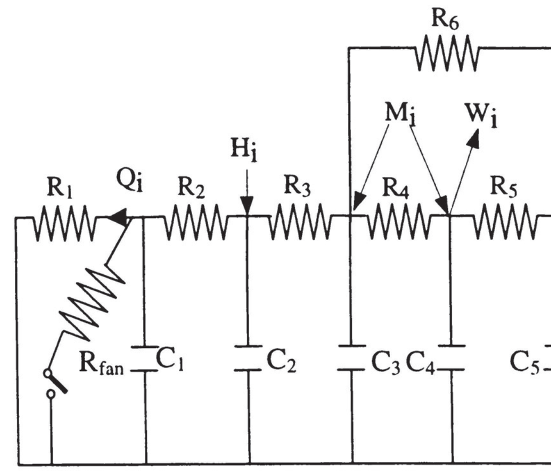

Fig.5 Equivalent electrical model for the zone *i*, *i*=1 to 7

All these would act as disturbances for the model and the control scheme and had to be taken into account in the model. For instance, the pressure changes reflect the volume flow changes, and hence, the temperature changes. Therefore, one important task has been to formalise the effect of the screw on the process, because as it has been mentioned in section 2, the screw introduces a heating effect that acts as a perturbation to the temperature controller. This effect has been taken into account by determining the amount of heat being generated by the screw in the different extruder zones.

Using the mass balance equations, the relationship between mass flow in the hopper and mass flow in the die has been analysed and the mass flow changes brought about by the changes in the screw speed have been evaluated.

The next stage has been to exploit the experimental data in order to perform the parameter identifications for each of the seven zones of the extruder.

A Simulink model (Fig. 6a) has been developed to simulate the behaviour of the different zones of the extruder and to identify the corresponding parameters. To do this, the model parameters have been first normalised and then optimised, using a quadratic criterion with higher weighting factors in the vicinity of the steady states.

For the complete model representation, the different zones have been connected. The dynamics of the temperature of the melt and the time delays have been incorporated. The polymer flow has been reconstructed from the screw speed. The resulting complete Simulink model of the extruder is shown in Fig.6b, where the rectangular block contains the model of Fig. 6a. It can be seen that the structure of the model makes it suitable for control purposes; the model can also be used for prediction. The

comparison between the experimental and simulated results is proposed on Figs. 7 (empty extruder) and 8 (full extruder), where the dotted line corresponds to the temperature set point (C^{O}) for zones 5, 6 and 7.
It can be seen that the model fits very well the experimental data both with empty and full extruder, even when disturbances in the temperature set point have been added. The model behaviour has been tested as well for different screw speeds for the experiment with full extruder.

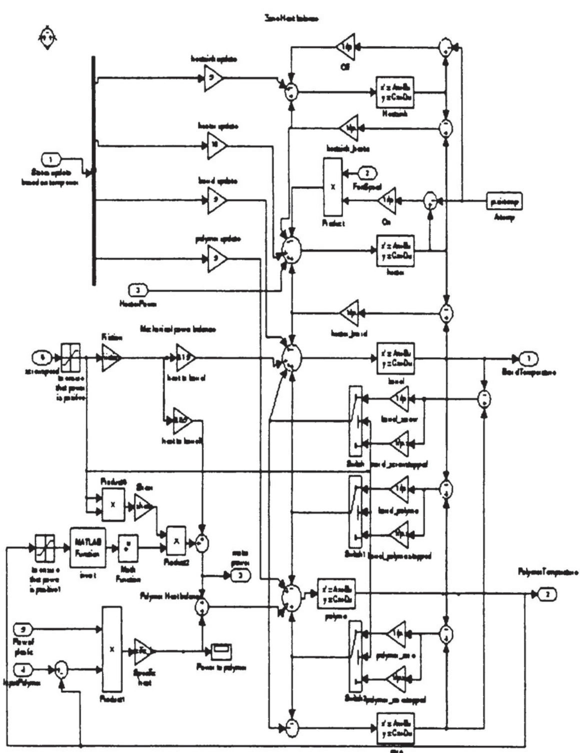

Fig. 6a Resulting Simulink model for each of the zones.

In the above model, the left side corresponds to the powers, and the right to the temperatures in the different states. The switches reflect the situation when the extruder is stopping. For the parameter identification, a constrained optimization to tune the coefficients was used; also, in order to optimise the identification, some of the coefficients were fixed to values derived from their physical meaning.

4. DISTRIBUTED CONTROL DEVELOPMENT

Different control strategies have been discussed and analysed, taking into account the specifics of the polymer processing (no overshoot allowed, minimum start-up and shut-down scrap etc) and the PSCI project requirements. A novel scheme has been developed, which is to be implemented on the plant at the next stage of the PCSI project. This multivariable control scheme is shown in Fig.9. For the purposes of our industrial application, this control scheme includes industrial single PC cards of the type PC 104, and PC3000 cards (programmable control system, specific to Eurotherm Ltd). Further, Control. Observer and Data logging functions are provided within a distributed (upper PC104/lower PC3000) configuration, necessary to demonstrate real time Java implementation. The three PC104/PC3000 realise the higher/lower level control of the barrel, flow, and line speed respectively. The PC 104 corresponding to the higher hierarchical level of control select the set points and the operating modes, they contain also the state observers. The latest take on the functioning of the lower level PID controllers (incorporated into PC3000) when there is an important measurement error.

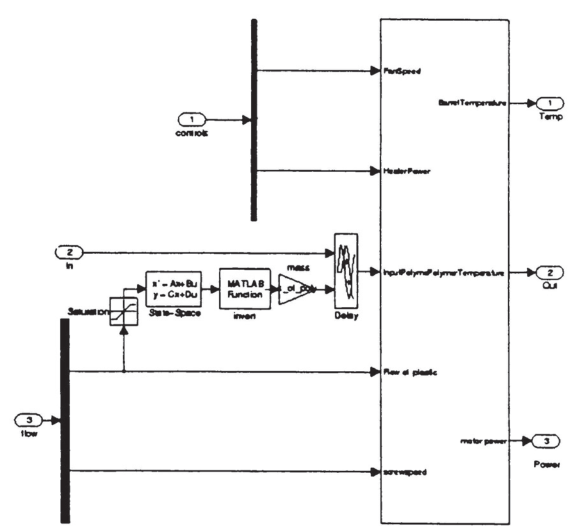

Fig. 6b Complete Simulink model for each of the zones

This control strategy includes the collection of data from the observers of the three sets of state variables: temperature, pressure, and mass flow. The observers run in parallel with the process, using the model developed in the previous stage. As mentioned previously, one important function of the observers is to replace the measurements from the real extruder, for instance when there is a sensor failure detected. The mass flow observer in particular is necessary, as there is no direct measurement of extruder flow, whilst the thermal observer has been incorporated to cope with the situation where a temperature

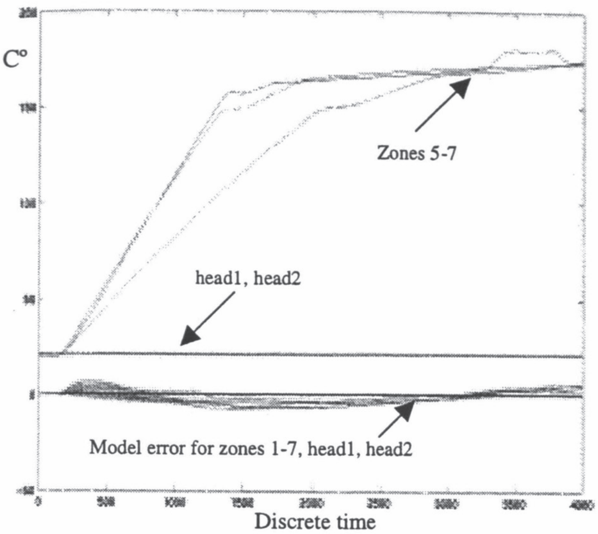

Fig. 7 Output temperature simulation and model error–trial without polymer

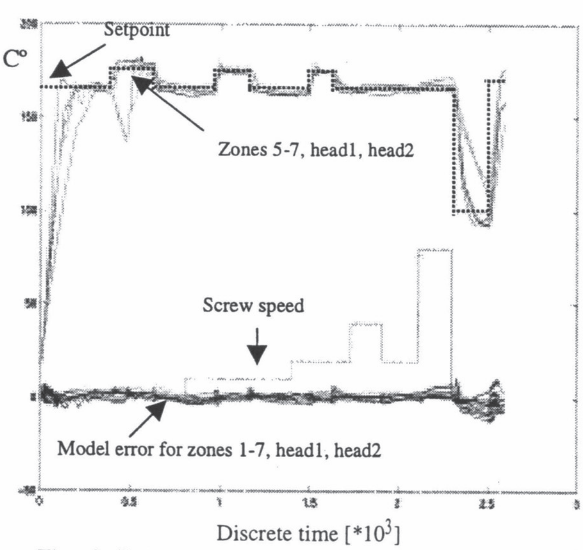

Fig. 8 Output temperature simulation, screw speed and model error–trial with polymer

measurement(s) is lost. The multivariable control scheme is at a higher hierarchical level of control, governing the local thermal, line speed, and flow rate controllers; at this lowest level we are essentially treating the extruder as three individual loops for the line speed, the pressure and the temperature. The multivariable controller also handles the co-ordination of set points, etc. The setpoint-trajectories replace (and also enhance) the ramping recipes that are currently use to raise/ reduce extruder output.
Another set of data is to be utilised as benchmark data from the current extruder control system.

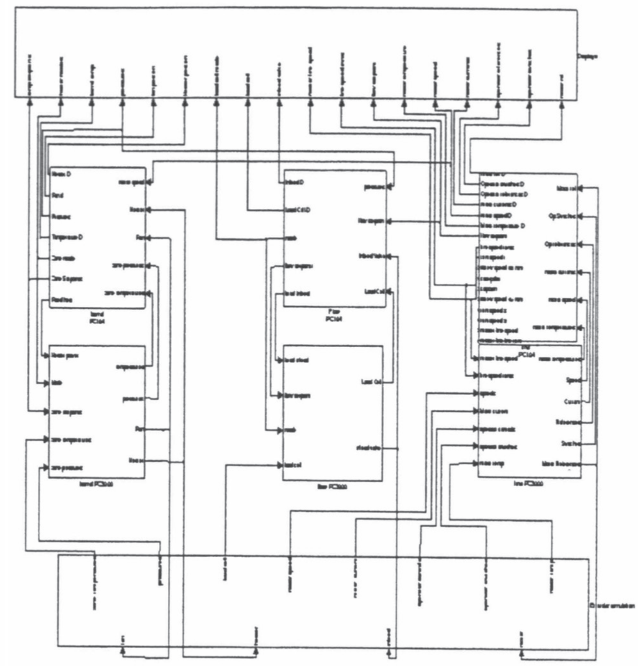

Fig. 9 Simulink model for the distributed control

In the next stage of the project, these results are to be used for evaluation of the revised control scheme.

5. CONCLUSIONS

A dynamic model and controller of a typical extruder have been developed as a part of the research project Process Control System Integration (PCSI). The model has been developed based on energy considerations and thermodynamics laws. The corresponding Simulink model has further been validated via experiments with empty extruder (without polymer) and full extruder (with polymer), and the matching between the measured and simulated data has shown to be quite satisfactory for both cases. A distributed control structure has finally been proposed taking into account the specifics of the polymer processing (no overshoot allowed, minimum start-up and shut-down scrap etc) as well as the PSCI project requirements.

6. ACKNOWLEDGEMENTS

This work is supported by EPRSC research grant No R09406625.

REFERENCES

Smith L. (1999) Modified Smith predictor for extruded diameter control, *Computing and Control Engineering Journal,* April, pp. 57-62.

McCrum N.G. and C.P. Buckley (1997). *Principles of Polymer Engineering*, Oxford Science Publications.

Keith, T and K. O'Brien (1992). *Computer Modeling for Extrusion and Other Continuous Polymer Processes*, Oxford University Press, New York.

Halasz L. (1993). Studies in Polymer Science 10, *Control Methods in Polymer Processing*, Elsevier.