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Nonlinear MPC for grade transitions in an industrial LDPE tubular reactor

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Abstract: A detailed physical model has been developed for an industrial 350 kt/year low-density polyethylene tubular reactor and implemented in a proprietary non-linear Model Predictive Control framework to control product quality during grade transitions. The controller is now at the end of the commissioning phase and is regularly used during transitions. Improved transition control reduces the amount of off-spec product, which improves the profit of the plant as well as the consistency during transitions compared to the manual transition control scheme used previously.

Keywords: model predictive control, process control, polymerization, tubular reactor, physical models

1. INTRODUCTION

Low-density polyethylene (LDPE) is an important polymer with applications ranging from packaging, bags, film to insulation material for wire and cables. LDPE is mostly produced in tubular reactors by free-radical polymerization at high pressure (2000 – 3000 barg) and high temperature (150 – 300°C).

Due to varying customer demand each plant is supposed to produce a portfolio of different product grades. When changing from one grade to another it is called a transition. During the transition the product is usually outside the specification of both the previous and the next grade, which means that it can only be sold to a much lower price. To improve the profit for the plant the amount of off-spec product for each transition has to be minimized.

There are a lot of different optimizations or decisions involved in transitions. At first there is a choice of the size of the product portfolio, what shall be produced in each plant. Secondly, in what order should each product grade be produced to minimize the transition time. Thirdly, how long should each product campaign last? The longer campaigns, the fewer transitions, but that requires more storage silos. Fourthly and finally, given the planned transition, how should all the inputs of the plant be changed to reach the new grade as fast as possible? This paper focuses on this last aspect.

LDPE from tubular reactors has been used in the industry for many decades and is the oldest technology in the polymerization industry. There has been a large number of studies and research devoted to design, modelling, optimization and control of LDPE tubular reactors. For modelling, see for example Kiparissides (2005). For optimal operation, see for example Logist (2008).

During normal operation the plant is at a stable operating point. The traditional control scheme is based on PID controllers implemented in the distributed control system (DCS), thus ensuring constant pressures and temperatures. Quality control is usually controlled manually by the operators by adjusting feeds or feed ratios based on continuous online or periodic offline measurements.

In the last decades the advances in Model Predictive Control (MPC) has also led to an interest to apply online optimization to the LDPE process, see e.g. the excellent work of Zavala (2009a) and Zavala (2009b) where moving horizon estimation and nonlinear MPC are used to control the reactor during varying fouling. However, they do not include the scope of transitions.

Optimal transitions for polymerization reactors have also been studied for a long time with different scopes and different control solutions. In Takeda (1999) transitions for two reactors in series are studied using detailed kinetic models and MPC. In Kadam (2007) an industrial reactor system is modelled using kinetic models, where the optimization is based on a method called "necessary conditions of optimality". Common for these and most other studies is that they are limited to simulations.

A very early contribution to transition control on real plants was described in Hillestad (1994). Here an earlier version of Borealis nonlinear MPC was applied on a real polypropylene slurry reactor to optimize grade transitions.

The contribution of this paper is that a very detailed physical model is developed and used within a nonlinear model predictive control framework in real life on an industrial plant. This means that the model has to include not only the reactor but also recycle flows, measurement delays, compressor dynamics and uncertainties in reaction kinetics. When going from a simulation study to real closed loop control in an industrial plant there are a lot of complications; from interfaces and logics between the MPC controller and the DCS, training board operators how to use the MPC controller and to make the controller robust for all uncertainties and all grades, yet fast enough to get the operators approval.

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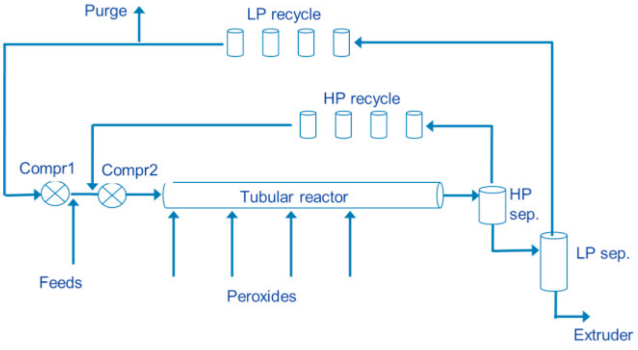

Figure 1: Simplified flow scheme of the LD5 plant

2. THE PLANT

2.1 The LD5 plant in Stenungsund, Sweden

The LD5 was started in 2010 and has a capacity of 350 000 ton per year. The LDPE produced in LD5 is mainly focused on the insulation for medium, high and extra high voltage cables up to the world record of 525 k. In these applications it is very important to satisfy the defined product specifications, since a cable failure will be very costly.

The LD5 process is outlined in Fig 1. The heart of the process is the reactor, which is 2400 m long. The reaction takes place at high-pressure (2900 barg) and high temperature (150-300°C). Organic peroxides are injected at four points along the reactor to initiate the free radical polymerization process. The reaction is exothermic so the reactor is cooled with a water jacket. The heat absorbed by the water is later used to produce low-pressure steam.

To reach the desired operating pressure there are two compressors, increasing the pressure from 0 to 275 barg and then from 275 to 2900 barg. Roughly 30% of the ethylene passing through the reactor is converted to polyethylene. After the reactor there is a high-pressure separator where most of the remaining ethylene is recycled back to the suction of the 2nd compressor at 275 barg to save energy.

There is also a low-pressure recycle after the low-pressure separator. Finally the polyethylene enters the extruder and is formed into pellets. The pellets are then dried, degassed and sent to a storage silo.

2.2 Control objectives

The most important control objective is to ensure correct and consistent product quality, that is, the product properties have to be within certain specifications.

The main feed is ethylene, also called the monomer. There is also a feed called chain transfer agent (CTA), which is used to control the polymerization reactions and influence how long the polymer chains are being produced in the reactor. There are many different chemicals that can be used as CTA, for example Propionic Aldehyde.

The most common product property is Melt Flow Rate (MFR). MFR can be seen as a measure of the average polymer chain length and an inverse measurement of the viscosity. Pellets with different MFR will have different mechanical properties and different processability in the customers' machines. The CTA feed is the main handle for MFR control.

In addition to the monomer and the CTA feed, there can also be extra co-monomer feeds. These could be other hydrocarbons with double-bonds, which may improve the product properties when incorporated in small-scale along the polymer chains.

The controller described in this paper has the following manipulated variables (MV) and controlled variables (CV). Due to confidentiality reasons the exact CTA and co-monomer feeds are not further described.

MV name (feeds)	CV name
Chain transfer agent	MFR
Comonomer 1	Content of Functional groups
Comonomer 2	Content of comonomer 2
Comonomer 3	Content of comonomer 3
Comonomer 4	Content of comonomer 4

MFR is a very complex property and is influenced by many parameters, such as reactor pressure, reactor temperature, monomer concentration, CTA feed and co-monomer feeds.

The amount of Functional groups is an indication on how reactive the polymer is for further downstream processing for the customer.

The co-monomer contents influence other properties that are important for the customer or the end user. Not all co-monomers are present in each grade.

The process is multivariable, where all feeds have a influence on MFR and both comonomer 1 & 2 have influence on the number of Functional groups in the polymer. The co-monomer contents are easier control objectives, since each co-monomer content is only depending on temperatures, reactor pressure and that specific feed flow.

2.3 Grade transitions

The recent trend in the process industry has been towards larger and larger production units. Older and smaller units are replaced with a newer larger unit. In Stenungsund, three old units were replaced by LD5, which has twice the output of the three old units combined. This improves the energy efficiency, but requires more transitions to keep the same product portfolio.

The recycle flows shown in Fig. 1 improves the steady state economics, but during transitions there is a large dynamic inertia in the recycle flows that makes the transitions challenging from a control and optimization point of view. This is one of the reasons why there is a large benefit in installing MPC for this process.