Real-time Optimization of Tall Oil Distillation using Model-Predictive Control

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ABSTRACT

Crude tall oil (CTO) is a by-product from pulp mills which can be further processed in tall oil distillation plants to provide valuable bio-based chemical products such as rosin and fatty acids. CTO is normally distilled in vacuum columns to avoid high temperatures whereby undesirable side-reactions will occur.

Forchem Oyj in Rauma, Finland has recently invested in an Advanced Process Control (APC) package which aimed at an increased production of the plant. The APC package chosen is a multivariable model-predictive control (MPC) solution with optimizing features such as maximization of CTO feed while respecting multiple dynamically varying process constraints. The MPC application is equipped with product grade change logic because three types of rosin is produced, and with an automatic calibration application for the product quality variables measured on-line are known to show some differences with respect to laboratory measured values.

The MPC application package was in guarantee runs demonstrated to be capable of keeping the production at an 8% higher level than is reasonably achievable by manual controls. The product quality is more uniform and the operation of the plant is more stable than before. Furthermore, the work of the control room operators has become much easier than before the MPC installation.

1 INTRODUCTION

Valuable bio-based chemicals can be obtained by processing crude tall oil (CTO). One of the processing options is to separate tall oil rosins (TOR) and tall oil fatty acids (TOFA) in a distillation process. Tall oil products are produced all over the world and the world market in year 2014 was estimated to be 400 000 tpy (tons per year) TOR and 380 000 tpy TOFA /1/. One of the biggest and also most modern tall oil distillation plants is owned and operated by Forchem Oyj in Rauma, Finland. The plant has a maximum capacity of 200 000 tpy CTO feed. Forchem recently finished an investment program which targeted at elevating the plant's capacity to the number mentioned above with low capital expenditure investments. As one of those investments, Forchem wanted to consider whether on-line real-time optimization (RTO) of the process could give them some benefits. The operators were skilled but operating the process included many manual control actions although most control loops were permanently on automatic mode. The grade changes, CTO total feed rate changes, overall material balance management and finally product quality control were performed by manual adjustments of setpoints of flow and level controllers.

This paper is organized as follows: in section 2 a short process description is given and section 3 outlines the control and optimization strategy as well as some implementation highlights. Section 4 describes the results achieved.

2. PROCESS DESCRIPTION

Water is removed from CTO feed pumped from feed storage tanks by heating, followed by a pitch removal stage which is based on vaporizing the CTO. Pitch is composed of heavy compounds which degrade the quality of TOR and TOFA and must be removed, but pitch has a (low) market value because it can be burned to produce energy. After de-pitching, the feed enters a distillation section which at Forchem consists of four vacuum distillation columns. Vacuum distillation is used to keep the boiling points in the columns at lower values, because at high temperatures, CTO, TOR and TOFA start to participate in harmful chemical side reactions such as degradation (de-carboxylation) of TOR into lighter rosins which are not desirable in the TOR product and on the other hand formation of bigger rosin molecules (dimerization) which are heavier and end up in the bottoms streams of the distillation columns instead of in the product streams. In the columns where TOFA concentration is larger, there is a risk for polymerization at higher temperatures.

The first distillation column (see figure 1) separates "crude TOR" and "crude TOFA", the latter being the lighter product and thus removed near the top of the column. Crude TOFA is sent to the heads column which removes the heads oil which is partly used to dilute the pitch and partly burned in the hot oil furnace. The bottoms from the heads column is fed to the fatty acids column from which TOFA is drawn.

The bottoms of the first column is sent to the rosin re-distillation column from which TOR is drawn close to the bottoms and distillate is drawn from a tray near the top. The bottoms of the re-distillation column is pitch.

All columns are equipped with reboilers using hot oil as heating medium. The circulating hot oil is heated up in a furnace which burns heads oil and ejector oil (oil coming from the vacuum system) so in terms of thermal energy the plant is self-sufficient.

Three types of TOR with different product characteristics (softening point) are produced in sequence, which means that product grade changes need to be done. The grade change involves adjustment of the TOR softening point target and multiple adjustments of the plant's overall material balance.

The qualities of crude TOFA rosin content - which is an impurity- and TOFA product rosin content are measured on-line by a Near Infrared (NIR) analyser. Softening point of the TOR product is on-line measured by a density correlation. Density correlations are available for also other streams in the plant, including the CTO feed. The plant has a high degree of automation and is operated using an Emerson delta V distributed control system (DCS) which uses fieldbus instrumentation.

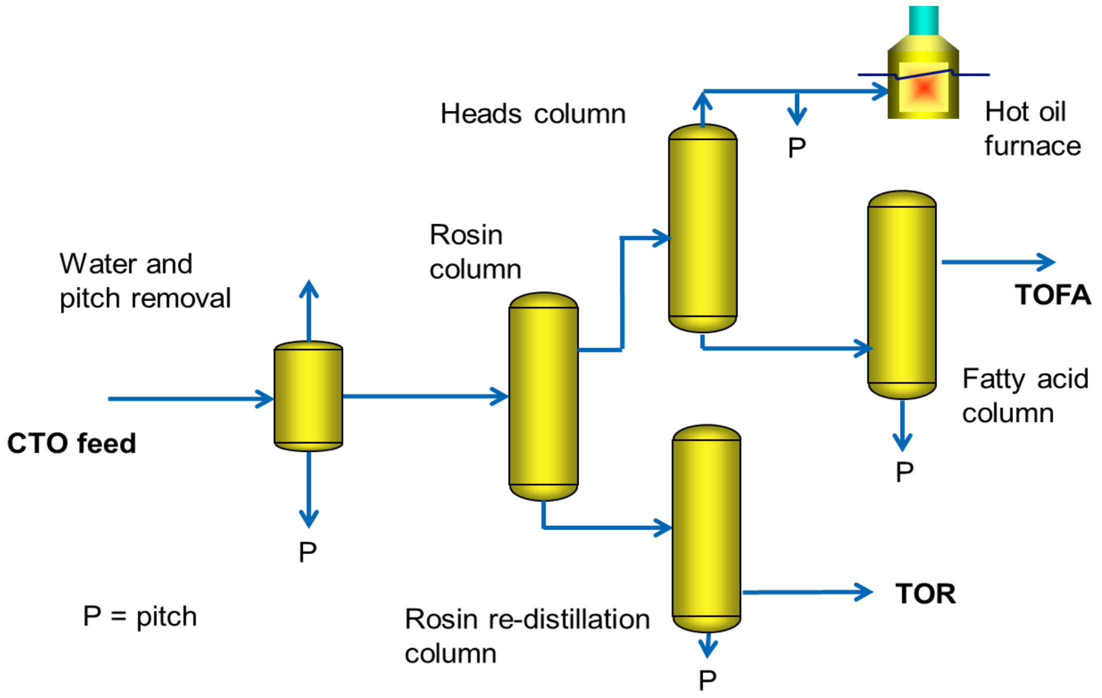

Figure 1. Schematic process diagram of Forchem's tall oil distillation plant

3 REAL-TIME OPTIMIZATION OF TALL OIL DISTILLATION WITH MPC

3.1 Real-time optimization and Model-predictive control

RTO is traditionally placed as a separate application above MPC and/or DCS in the automation hierarchy. This is also true in cases where Dynamic Real-time Optimization (DRTO) is being used instead of the steady-state based RTO [2]. MPC has always contained optimizing features like pushing process variables towards constraints from which more optimal operation follows, and more can be done in order to achieve full-blown economic optimization by MPC [3]. In conclusion, it is motivated to say that MPC has nowadays turned to a flexible tool, with a selectable degree of real-time optimization of process economics in it. The application at Forchem is close to a standard MPC with field-proven constraint handling capability and flexibility to handle different changing process conditions.

3.2 Performance Analysis

It is highly recommendable to study the plant by a Performance Analysis (PA) prior to implementing MPC. The most important results of a PA are estimates on the benefits achievable (in terms of profit increase, increased efficiency, decreased energy consumption, etc.) and implementation cost estimate. This should identify not only the costs directly related to MPC but also costs related to necessary renewal of instrumentation, on-line analysers, DCS, and even process equipment. This valuable information reduces the risks of costly surprises during the implementation. The PA also typically reveals attractive small improvements for instance in DCS control loops which may provide a surprisingly good benefit. Finally, the PA should define the preliminary control strategy (see section 3.3) because this is also the basis of the MPC package cost estimate.

The PA made for Forchem concluded that the process and instrumentation was in a good shape and no other costs would be incurred than the MPC package implementation cost. A process test done during the PA revealed that careful manual operation, where process constraints are logically relaxed, could give some 8% increased production. Another 8% production increase was estimated to be achievable by MPC.

3.3 Control Strategy

The control strategy developed during the PA was an overall material balance maintaining strategy with continuous pushing of plant feed against varying constraints and local maximization of TOR and TOFA product against product specification limits. In addition, the temperature of fresh hot oil to column reboilers and other consumers would be dynamically minimized when constraints allow in order to minimize energy and increased if production maximization required more energy input from the hot oil system.

The control strategy covers almost the whole plant from the CTO feed to the outlets of the TOR and TOFA products. When the production is maximized, the controller continuously monitors possible varying bottlenecks (constraints) in the process and looks for opportunities to increase the CTO feed further. When dynamically changing constraints are predicted to be violated the controller adjusts the CTO feed in advance. In this way, stable operation of the plant can be maintained simultaneously as the production is continuously maximized. The control strategy materializes in the individual columns as follows:

1) Rosin column: The rosin content of the crude TOFA shall remain on a constant level simultaneously as certain known process disturbances are allowed to temporarily violate the rosin content without any controller action. In addition, MPC controls the reboiler level.

2) Heads column: very well controlled by DCS elementary control loops. Only the crude TOFA feed to the column is manipulated by MPC

3) Fatty acid column: Shall give as much TOFA product as possible without violating the rosin content maximum constraint of the TOFA product.

4) Rosin re-distillation column: Planned controlled strategy was similar to the strategy of the fatty acid column, i.e. maximize TOR production against minimum softening point constraint. However, the column was too sensitive for this kind of operation and its controls needed to be re-designed during the commission phase. More attention regarding the mass balance of the column was needed in order to maintain stable column behaviour. The new strategy for this column was designed by introducing some extra supporting process calculations that helped the controller to maintain stability. Also tuning and reconfiguration of the DCS controllers at the bottom part of the column improved the stability issues.

The matrix of dynamic models identified from process data is sparse (as it usually is). However, the inputs to the model of TOR softening point (manipulated and disturbance variables) approached 10 during the modelling phase but was subsequently decreased to 6 and one clearly dominating manipulated variables in the rosin re-distillation column was found. This was also otherwise the most demanding model due to large drifting disturbances in measured process data.

The MPC recognizes a rosin grade change based on the crude oil feed ratio set by operators. The ratio is determined by operators and then MPC automatically changes the target for the softening point and all other parameters.

3.4 Correction of on-line product quality measurements with Automatic Calibration

The quality of the Forchem TOR and TOFA products are very important and therefore the values supplied to MPC as measured variables to be controlled should be as accurate as possible. The on-line measurements - NIR analyzer and density correlations - of product qualities provide information about the current condition of the process. During the PA the NIR analysers were observed to depart from laboratory data so the idea of an Automatic Calibration (AC) application was developed. An automatic procedure is implemented to use laboratory analysis results with which the corresponding on-line quality variables are updated. The update procedure is a smooth filtering procedure of which the filtering strength, which reflects the confidence on laboratory vs. on-line measured value must be tuned with great care. In practice, AC performs a level or "bias" correction where the strength and speed of correction depends on the filter parameters. The application, which is a calculation module integrated with MPC, is connected to the Laboratory Information Management System (LIMS) of Forchem and captures the laboratory analyzed values as soon as they are entered into the LIMS and then performs the filtering calculation, see figure2.

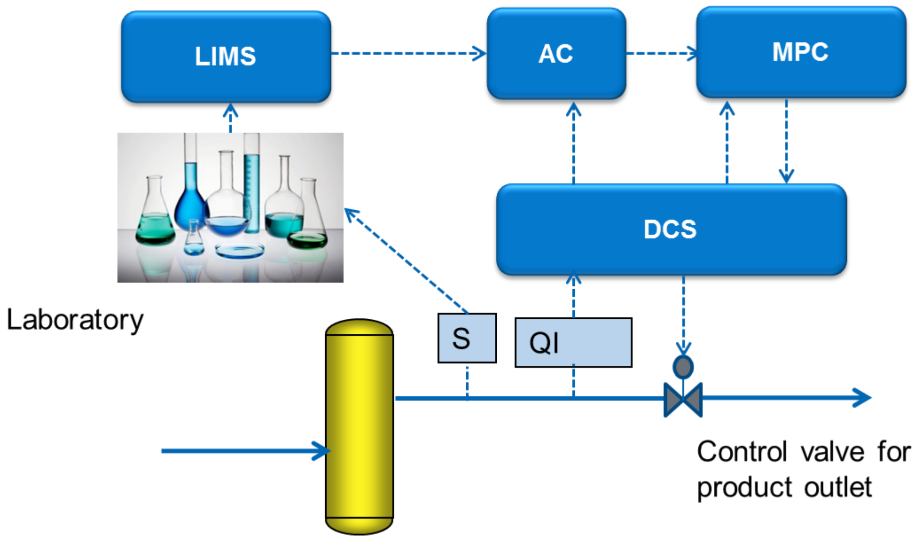

Figure 2. Working principle block diagram for AC. QI = on-line product quality measurement (NIR or density), S = sample point for laboratory

3.5 Project Implementation highlights

If substantial benefits are expected out of an MPC implementation, it is essential that the project schedule supports harvesting of the benefits quickly.

The implementation work started with preparation of a Functional Design Specification (FDS) and simultaneously the detail design of the DCS and LIMS networking with the MPC computer server was started. The typical MPC implementation steps: process step tests, modelling, MPC configuration and pre-tuning in a simulation test bench started after the FDS was approved by Forchem. It was possible to commission a part, namely, control of TOFA production, with an accelerated schedule, so called "Early Start", which happened 5 months after start of implementation work. The commissioning of the rest of the application (TOR production, CTO feed maximization, hot oil system) started 7 months after start of implementation work. At 8.5 months after start the guarantee run was performed which confirmed that the MPC application was fully capable of maximizing the production. At this point, the implementation was de facto completed, but it had been originally agreed with Forchem that a follow-up period of four months was needed to follow up over the summer period because it was assumed that warm summer weather would have a drastic effect on the vacuum system which would impact the MPC with some requirements on re-tuning. Forchem also utilized this period by requesting operator training to be done after the summer.

There are natural temporary disturbances in CTO feed where the substance composition varies. As an extra MPC-feature a soft sensor for detecting abnormal high rosin content in the CTO feed was implemented. It is used for temporarily freeze the control action for the rosin content in the crude TOFA which in turn prevents the MPC from control actions that may swing a great part of the whole plant unnecessarily.

As was mentioned earlier in the text, the control strategy for the rosin re-distillation column needed to be remodelled during the project. The existing DCS control loops did not take care of the overall mass balance of the column and this was successfully established as a part of the MPC during the commissioning phase.

A remote connection to the MPC was set up in order to quickly establish a connection between MPC experts and the actual controller application if for example something needs to be reconfigured or retuned. The performance of the MPC application is also monitored remotely.

4 RESULTS OF THE REAL-TIME OPTIMIZATION PROJECT

The guarantee test showed that MPC can run the process at an elevated CTO feed level which is 8% higher than can be maintained by manual operations. In addition, the yield of TOFA increased by 1.5 %-units. TOR yield did not increase because the rosin re-distillation column has such a process design that the "normal way" of maximising product output flow against product quality limits was not possible.

The TOR product grade changes are almost fully automatic. Default values for the softening point of the two product grades have been introduced that automatically activates when the feed ratio target changes and exceeds a certain limit, i.e. actually the grade change only need one manual parameter input.

After MPC implementation it is also easier to adjust the production of rosin and fatty acid for example to changing market conditions. If there is a higher demand for one of the products the production can easily with just a few manual inputs be changed to favour this product. For example by raising the target for the rosin content in the crude TOFA, more fatty acid is produced on the expense of the rosin product. Also otherwise the normal operation of the plant require very little manual interventions after implementation of MPC which has been highly appreciated by the whole Forchem personnel.

For more information on the MPC product used in the application described in this paper , see /4/.

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