Applying MPC to a Batch Process

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ABSTRACT

The application of Model Predictive Control (MPC) is often considered for multi-variable continuous processes. However, the benefit of applying MPC to a batch process can often be just as significant as a continuous process. In this presentation we will show how MPC is being applied in a pharmaceutical manufacturing facility for the control of one cut of a batch distillation column. The primary benefit of using MPC is to reduce batch cycle time. The performance that can be achieve with MPC vs. traditional techniques for this application will be examined.
APPLYING MPC TO A BATCH PROCESS

Model Predictive Control (MPC)

Model Predictive Control, (MPC), is a method of control that utilizes an internal process model to determine the impact of one process variable upon others. This prediction across multiple control loops means that loops not yet directly affected by the disturbance can begin to react ahead of time, minimizing the disturbance. Additionally, MPC allows the optimization of variables, which allows the maximization or minimization of variables within the constraints imposed. For the most part, MPC has been utilized on continuous processes. However, certain batch applications can also benefit from MPC. This paper discusses the application of MPC to the batch distillation of one cut of an intermediate product at a pharmaceutical facility.

Background

The process selected for this application is a batch pharmaceutical facility that produces inhalant anesthetics using a series of reactions and distillations. The application has two high-pressure process reactors, each with its own distillation column, jacket heating and cooling equipment, and a pair of condensers mounted in series. These two reactors are mechanically identical, and will be referenced as one application throughout this paper. Through an exothermic reaction, the reactor produces the raw materials that are later distilled as intermediates and recycled products. When the reaction is complete, the product is distilled into two product cuts, and two intermediate cuts. One of the product cuts was chosen for the MPC application, as it was the longest time duration of the distillations.

This distillation cut has been controlled in various ways for the past 10 years. These methods have utilized various combinations of traditional PID control. The distillation has always been reasonably successful, with acceptable product yield and quality, but with extended cycle times. Additionally, the means used to control the cut have been very operator intensive, which would also cause impacts to the cycle times and yield. The most recent method of control is shown in Figure 1, and described as follows: The overall traffic through the column is controlled by a boil up controller, which controls the amount of heat energy provided to the reactor jacket. More heat produces more boil up, and more traffic through the column. Past experience and the rating of the column determined the typical boil up setpoint, which is kept constant throughout the cut. A reflux or return flow transmitter provides the measurement of the return distillate flow to the column. A takeoff flow measurement and control provides the main manipulated variable. A mid column temperature reading provided the main distillation product temperature variable. Other measurements, such as various column temperatures, vent temperatures and pressures, and column differential pressure, are also available, but normally only used if they go into alarm.
PID Distillation Control

Figure 1
To control the column, the operator would first set the boil up controller setpoint to a set value, which provided a relatively constant traffic through the column. Then the operator would observe the mid column temperature, and, with the knowledge of where in the historical cut cycle was located, set the takeoff flow controller setpoint to a flow value. In the early part of the cut, the composition of the product in the reactor would have a large percentage of the desired cut, and would allow a larger takeoff flow setpoint. As the cut progressed, the operator reduces the takeoff amount, resulting in a larger reflux flow, and keeping the temperature within the operating range. If the operator waits too long before reducing the takeoff flow setpoint, the mid column temperature can exceed the temperature specification, and a solenoid valve would shut off the takeoff of product. This control resulted in a stepwise adjustment of the takeoff flow controller setpoint, with adjustments typically being 0.5 to 1 hour apart, depending upon the confidence and experience of the operator. At some point the operator would decide, based upon the amount of material collected, that the distillation was complete.

The decision was made to apply MPC to this process. Given the length of the distillation cut, it was felt that the process would behave in a somewhat continuous fashion. The main concern, and batch aspect of the process, was the changing composition of the product in the reactor over the distillation cut. The traditional method of control using a fixed ratio between the reflux (return) flow and the total (return plus takeoff) flow would not work by itself, as this ratio would change over time. Additionally, it was felt that the mid column temperature would ramp up slowly over the cut based upon the changing composition in the reactor, no matter the control method.

There were two additional user requirements on the use of MPC. One was validation, which is faced by all pharmaceutical manufacturing facilities. The second was that this project was a retrofit of a DCS, which meant that the previous method of control would need to be put in place to start with, and MPC control provided as an on line switch-able option. This would allow the plant to start up and resume production with the traditional control, with no additional training or Standard Operating Procedure (SOP) changes, and phase in the MPC at a later date. These two requirements, as much as any of the other controls considerations, led to the MPC solution chosen.

**Development of the MPC Application**

The development of an MPC application requires several steps. A typical procedure of MPC application development consists of the following steps:

- Process analysis
- MPC configuration development
- Testing the process to develop the process model
- MPC simulation and tuning validation
- MPC control evaluation and tuning adjustment

The utilization of the above steps as applied to the batch distillation cut follows. The DCS installed in the plant had MPC tools integrated with a standard configuration and operation environment, streamlining the development process.
Process analysis delivers a clear formulation of process control objectives and limitations as well as means of achieving those objectives. In other words, process analysis results in process configuration in MPC terms. The result of the process analysis of the batch distillation is shown in Figure 2.
MPC Distillation Control

Figure 2
MPC configuration development started with the existing PID control. This was done based upon several of the process constraints. The result was a straightforward mechanical and conceptual switch between MPC and PID control.

The process inputs and outputs were grouped into four different categories based on how they are utilized in the control of a process:

*Manipulated* (MV) – Product ratio and boil up.

*Controlled* (CV) – Mid column temperature

*Disturbances* (DV) – Rate of column bottom temperature change.

*Constraints* (AV) – Vent temperature and column pressure.

*Optimized* – boil up was set to be maximized.

Testing the process to develop the process model was not possible in this batch application due to the high costs of raw materials and the highly regulated environment, which prohibit wet runs of process; therefore the initial process model was developed from the operational historical data. The model was verified and corrected based on verification errors and the resulting model was used for MPC controller development.

MPC control simulation and tuning validation. The process response was tested based upon a process model developed from process data collected by the data historian. By using this model, it was possible to test the control response for changes in the process.

The ability to introduce disturbances and test the control for changes in process gain or dynamics is extremely valuable in the provision of a robust control scheme. If the process response is too aggressive, it is easy to improve results by modifying the default MPC controller settings for the Penalty on Error, the Penalty on Move, and the setpoint filter.

MPC control simulation also allows the speed of execution to be adjusted, allowing quick verification of changes to the model. The simulation uses normal MPC operating interface.

MPC control evaluation and tuning adjustment. Control evaluation during normal operation is essential, especially if the initial model is developed manually from operational data, as ours was. Criteria such as the prediction horizon, relative time constants, gains, and filtering need to be evaluated under a variety of conditions to determine if they are appropriate. It is important to note that a batch process will have a variable and sometimes non-linear gain, so optimization of some parameters will be required. With some care, adjustments of the model can be done during the execution of the batch.

Installation and Startup

The MPC model was developed using the above methodology. The MPC control scheme utilized the underlying PID control, with the addition of an MPC control function block. The MPC application, as shown in Figure 2, provides control of the boil up as an optimized (maximized) variable, control of the mid column temperature by adjusting a takeoff ratio controller (takeoff ratio is the ratio of the takeoff flow to the total flow), which in turn adjusts the takeoff flow. The vent temperature and pressures are used as constraints, and the lower column temperature rate of change is used as a disturbance.
The developed model was installed in the controller, using the initial tuning from the simulation. Through the course of 6 days, utilizing a slightly different model on each of the two reactor/columns, the control was observed and adjusted. A total of seven process cycles were run on the two reactors/columns. The operators, who were quite accommodating throughout the whole process, saw about a 50% reduction in the amount of adjustments and attentions necessary to control these processes. As of this writing, the average cycle time for the distillation cut was reduced by 19% (Table 1). Since the cycle time reduction occurs in the actual capacity constraint reactor, the impact results immediately in total capacity increase of the plant. A 19% cycle time reduction results in an average plant capacity increase of 5.4% or approximately $2MM in product without a major capital investment in equipment or expansions.

<table>
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<th>MPC</th>
<th>PID</th>
<th>Difference</th>
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<td>17:23</td>
<td>2:03</td>
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<tr>
<td>2</td>
<td>15:22</td>
<td>17:39</td>
<td>2:17</td>
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<td>15:37</td>
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<tr>
<td>Average</td>
<td>14:40</td>
<td>18:01</td>
<td>3:21</td>
</tr>
</tbody>
</table>

Table 1. Distillation Cycle time in HH:MM.

Once the tuning was completed, the following observations were made:

1. MPC is meant to be an optimization tool for processes in steady state, and such the process must be stabilized prior to placing it in control. This is a critical factor, as the batch distillation is of a finite time, and the tendency is to turn it on too soon. Therefore, enough time needs to be allocated at the beginning of the batch cycle to stabilize the process (in our case boil up control).

2. The underlying control (in this case mostly the boil up) has to be well tuned. Although this seems to go without saying, it was more critical in this application. As the MPC adjusted the takeoff ratio, which was normally \(\leq 20\%\) of the total flow (boil up + takeoff), the MPC could only fractionally adjust any deviations that boil up caused. Therefore, if boil up cycled, MPC was unable to compensate.

3. All factors associated with the process should be considered. In our case, the control loop that controlled the jacket steam temperature was not included in MPC. Adjustments to this temperature cause changes to boil up that were, to MPC, unmeasured. This would also end up causing problems with items 1) and 2) above.

4. The temperature control worked well. Over time, the temperature setpoint setting was determined to be somewhat below the temperature specification value (at which the solenoid valve would interlock). The natural tendency of the mid column temperature was to go up over the duration of the batch, so temperature excursions above the setpoint were much more difficult to overcome than deviations below the setpoint.
5. Due to the impact of boil up changes to MPC, no optimization of boil up was implemented. The boil up setpoint was set to a predetermined value based upon the column design. Although this value may be adjusted from time to time, it will probably be set at the beginning of the batch and not changed. Additionally, the constraints for vent temperature and pressure, and the disturbance for the rate of change of the column bottom temperature were not implemented. Based upon the observations of the process, the vent temperature and pressure did not react consistently during normal operation. They normally only apply when the column is flooded, which was not observed. The column bottom temperature rate of change also did not seem to react in a consistent fashion during normal operation.

6. As is the case with all control strategy changes, operator training and education is critical. However, with the level of education prevalent in the pharmaceutical industry, and the fact that MPC will generally unload the operator, MPC implementation on this process was an easy sell.

Conclusions

MPC can be successfully applied to batch applications. The main criterion for use was that there was sufficient time in the batch process to stabilize and optimized. Our process has a batch time of between 10 and 20 times the process time constant. Other criteria of importance would be the definition of the control, and the ability to model the process. Certain batch processes will have non-linear gains, which can be difficult to model. It is important to include any process measurements into the model that will impact the control (the example in our case is the steam temperature control). If these measurements are not included, no prediction will occur for that variable, and the control can only react.