Optimizing Robust Model Predictive Control of Industrial Reactive Stripping Process System


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Abstract
The paper deals with the design and application of optimizing robust model-predictive controller (ORMPC) for the industrial reactive stripping process system (nitrogen treatment plant) located in Samsung Fine Chemicals Co., Ltd. The elimination of nitrogen up to the given concentration in the waste water is the main purpose of T-N plant. The latter consists from the two coupled reactive stripping towers with the following urea decomposition reaction: \( \text{urea} + \text{H}_2\text{O} \rightarrow 2\text{NH}_3 + \text{CO}_2 \). From the control point of view the investigated plant is multivariable and strongly nonlinear having at least 4-by-4 temperature control configuration excepting the levels and pressures control loops. The application of PID-controllers caused a poor performance, often violation of the nitrogen isolation limits and steam overexpenditure. In order to solve these problems the process model was evaluated for predictive control in the frame of Profit Controller software package (Honeywell, Hi-Spec Solutions). It was proposed to control optimal temperatures profiles of the columns ensuring the minimum steam consumption and nitrogen concentration admissibility in the final product in spite of unknown feed composition disturbances.

Keywords: model predictive control, reactive stripping, dynamic optimization

1. Introduction
The energy saving is a topical problem in the chemical industry. Its solving depends from the performance of the control system. The present paper deals with an industrial reactive stripping plant (RSP) located in Samsung Fine Chemicals Co. Ltd. It contains two interconnected columns (fig. 1) involving decomposition of \( \text{CO(NH}_2\text{)}_2 \) (urea) concurrent with separation (stripping) of the reactions products. The main product (bottoms, B) of the plant is cleansed water with given content of nitrogen fed to cogeneration plant for steam production. Therefore, its quality control is very important.

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The additional product (distillate, D) is aqueous solution mainly containing carbon dioxide, ammonia and recycled to the urea plant.

The model predictive control (MPC) technology is a widespread technique used in the chemical industry for control of multivariable plants. There are several tools like RMPCT, DMC, SMOC and etc. (Qin and Badgwell, 2003). The success of application of these packages depends from the evaluated process model. The assumption of the linearity of the process model often is not valid in practice. Therefore, the model selection is important step for advanced control system application. The present work shows the model evaluation procedure and MPC system application experience for industrial RSP using RMPCT (Honeywell) platform.

### Figure 1: Reactive stripping plant

#### 2. Process Model Evaluation

The investigated plant consists from the two columns T901 and T902 (Fig. 1). The nominal process parameters measured in on-line mode are cited in Table 1. The ratios among the flowrates are taken in order to reduce amount of analysed process variables.

<table>
<thead>
<tr>
<th>compound</th>
<th>stream</th>
<th>fic901</th>
<th>D</th>
<th>B</th>
<th>fic903</th>
<th>fic904</th>
<th>fic905</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO(NH$_2$)$_2$</td>
<td>3325·10^{-4}</td>
<td>284·10^{-4}</td>
<td>2·10^{-4}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH$_3$</td>
<td>3.13</td>
<td>26.65</td>
<td>21·10^{-4}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO$_2$</td>
<td>0.81</td>
<td>10.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$_2$O</td>
<td>95.7</td>
<td>63</td>
<td>99.99</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>
The fee d flow (plant load) enters on the 6 tray of T901. It is the mixture having the composition presented in Table 2. The flow B is the main product. It quality stabilization ($N_2 \leq 60 \cdot 10^{-4}$) is so complex problem because the execution time period of on-line analyzer is 30 min. Moreover, the analyzer often produces the measurements with high error. The lack of information about the content of $N_2$ leads to an increase of steam consumption (fic903, fic904 and fic905). There is necessary to develop two types of models in order to control optimal RSP operation:

1. The evaluation of transfer matrix for ORMPC implementation based on the platform of Profit@Controller (Honeywell).
2. First-principle modelling (mass transfer, chemical interaction) for determination of interrelation between process parameters and concentration of $N_2$.

The step tests of industrial plant were used for first model development. The several transfer matrices were investigated. As the result, the following transfer matrix was derived with minimum condition number on the interesting frequency range (Fig.2):

\[
G(s) = \begin{bmatrix}
DV, \text{fic901} & MV_1, \text{fic902} & MV_1, \text{fic904} & MV_1, \text{fic905} \\
CV_1, \text{TIC901} & -0.51 & -0.03 & -0.126 & 3.17 \\
CV_2, \text{T903} & 0.126 & -0.367s + 1 & -4.83s + 1 & 2.3s + 1 \\
CV_3, \text{T905} & -4.83s + 1 & 28.9s^2 + 17.4s + 1 & 0 & 8.81s^2 + 3.67s + 1 \\
CV_4, \text{T913} & 0 & 0 & 0 & 0
\end{bmatrix}
\]

where CV, MV and DV – controlled, manipulated and disturbance variables respectively. The model (1) was less sensitive for interaction among the single control loops.

The main obstacle for the second type model evaluation is caused by the presence of chemical reactions (Wicar, 1963):

\[
\begin{align*}
\text{NH}_3 + \text{CO}_2 + \text{H}_2\text{O} & \leftrightarrow \text{NH}_4^+ + \text{HCO}_3^- \\
\text{NH}_3 + \text{HCO}_3^- & \leftrightarrow \text{NH}_2\text{COO}^- + \text{H}_2\text{O} \\
\text{NH}_3 + \text{HCO}_3^- & \leftrightarrow \text{NH}_4^+ + \text{CO}_3^- \\
\text{NH}_2\text{CO-NH}_2 + \text{H}_2\text{O} & \leftrightarrow \text{NH}_2\text{COO}^- + \text{NH}_4^+, 
\end{align*}
\]
for which the chemical equilibrium constants represent nonlinear functions from temperature. They are not exactly defined for all range of process parameters (Kotula, 1981). Certain of the equilibrium constants equation parameters for reactions (2) can be found in the works of Bieling et. al., 1989 and Bernardis et. al., 1989.

It was difficult to use the rigorous phase equilibrium model of quaternary mixture with chemical interaction for the purpose of industrial RSP steady-states simulation and optimization because of the large errors of flowmeters, long time data reconciliation procedure and model parameters fitting for current operating point. Therefore, we found the correlation between the urea conversion and temperature in T902 (Fig.3) and that ammonia concentration has the strong influence on the \( N_2 \)-concentration in B (Fig.4). Finally, the optimal temperature profile (TIC901, TI903, TI905 and TI913) was determined for the provision of stabilization of \( N_2 \) concentration in the given range based on the reduced \((NH_3-H_2O-CO_2)\) mixture thermodynamic properties and estimates of urea conversion.

Table 2: Nominal process parameters

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Unit</th>
<th>Nominal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reflux ratio, fic902/D</td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>2</td>
<td>Streams ratio fic902/fic903</td>
<td></td>
<td>0.29</td>
</tr>
<tr>
<td>3</td>
<td>Streams ratio fic902/(fic904+fic905)</td>
<td></td>
<td>0.64</td>
</tr>
<tr>
<td>4</td>
<td>Streams ratio fic902/fic901/0.01</td>
<td></td>
<td>3.6</td>
</tr>
<tr>
<td>5</td>
<td>Streams ratio fic903/fic901/0.01</td>
<td></td>
<td>12.3</td>
</tr>
<tr>
<td>6</td>
<td>Streams ratio fic904/fic901/0.01</td>
<td></td>
<td>4.65</td>
</tr>
<tr>
<td>7</td>
<td>Streams ratio fic905/fic901/0.01</td>
<td></td>
<td>1.06</td>
</tr>
<tr>
<td>8</td>
<td>Streams ratio D/fic901/0.01</td>
<td></td>
<td>11.69</td>
</tr>
<tr>
<td>9</td>
<td>Temperature, TI908</td>
<td>°C</td>
<td>37.4</td>
</tr>
<tr>
<td>10</td>
<td>Temperature, TIC901</td>
<td>°C</td>
<td>124.9</td>
</tr>
<tr>
<td>11</td>
<td>Temperature, TI903</td>
<td>°C</td>
<td>137.8</td>
</tr>
<tr>
<td>12</td>
<td>Temperature, TI905</td>
<td>°C</td>
<td>207</td>
</tr>
<tr>
<td>13</td>
<td>Temperature, TI913</td>
<td>°C</td>
<td>208.8</td>
</tr>
<tr>
<td>14</td>
<td>Concentration of ( N_2 ) (% mass) (10^4)</td>
<td></td>
<td>20.3</td>
</tr>
</tbody>
</table>

3. RMPCT Application

The implementation of RMPCT-controller was in the optimizing mode (Honeywell, 2001). The optimization problem was considered by the following criterion:

\[
J = a_1 \cdot \text{fic903} + a_2 \cdot (\text{fic904} + \text{fic905}) \rightarrow \min
\]

(3)

under temperature profile constraint:

\[
\text{TIC901}^L \leq \text{TIC901} \leq \text{TIC901}^H \\
\text{TI903}^L \leq \text{TI903} \leq \text{TI903}^H
\]
\[ \text{T} \text{I}90^5 \leq \text{T} \text{I}90^5 \leq \text{T} \text{I}90^5 \text{H} \]  \quad (4)
\[ \text{T} \text{I}91^3 \leq \text{T} \text{I}91^3 \leq \text{T} \text{I}91^3 \text{H} \]
and product quality requirement:

\[ \text{N}_2^L \leq \text{N}_2 \leq \text{N}_2^H \], \quad (5)

where \( a_1, a_2 \) – weighting coefficients depending from the steam flows costs; \( L, H \) – indexes associated low and high limits of the variable respectively. Based on the first-principle model the temperatures constraints (4) were obtained in order to fulfil inequality (5). It was found that the minimum value of criterion (3) was attained under high limit of \( \text{N}_2 \) concentration, i.e. \( \text{N}_2=\text{N}_2^H \).

Figure 2: Condition number of transfer matrix minimization. “o”-model with minimum condition number

Figure 3: Estimation of urea conversion from temperature in T902 (relative units)

Figure 4: Impact of ammonia for \( \text{N}_2 \) concentration in B (relative units)
Figure 5 shows commissioning results of ORMPC system with achieved benefits (total steam saving). The derived improvement for N$_2$ concentration control performance are presented on the Fig. 6.

![Comparison analysis of total steam consumption](image1)

**Figure 5: Comparison analysis of total steam consumption**

![Nitrogen concentration control performance improvement](image2)

**Figure 6: Nitrogen concentration control performance improvement**

### 4. Conclusion

The present work demonstrates an application of advanced process control tools in order to get more benefits from the industrial plant operation. The dynamic optimization problem was solved using RMPCT. The optimal steady-states were predicted based on the first-principal model in off-line mode. The total steam consumption was considered as RSP optimization criterion under product quality constraint.

### References

Wicar S., British Chemical Engineering, 1963, 8, 12, 818.