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On Applying Model Predictive Control for Carbonation Towers in Manufactory of Soda Ash

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Abstract: The carbonation process of Solvay’s soda plant is essentially a Multi-Input-Multi-Output (MIMO) system with strong coupling among process variables, severe disturbance and process nonlinearity. Classical control structure with multi-loop PID control usually cannot maintain a long-time stable control in the practical process. This study introduces industrial application via a commercial software of MPC for three blocks of carbonation towers in a soda plant which consists of fifteen carbonation towers, A MPC system constructed of controlled variables, manipulated variables and disturbance variables, was developed to deal with the constrained multivariable control problem on-line of the carbonation towers. Industrial application results have shown that the MPC software can maintain the best operation for a long time and realize ultimate operating potential of the carbonation systems by reducing the consumption of material, improving product quality and minimizing operating cost.

Key words: Model predictive control, industrial application, carbonation towers

INTRODUCTION

Sodium carbonate, often-called soda ash, is a commodity chemical used in several branches of industry. The glass industry is the largest user of soda ash which is also used in production of other chemicals, such as study industry, detergents and cleaners and in water treatment. Soda ash can be produced either synthetically or through the processing of trona or brines. The Solvay process, also called ammonia soda process, is the dominant synthetic method used in the world to manufacture soda ash today.

In 1861, Ernest Solvay perfected a soda ash production technique based on common salt (NaCl), limestone (CaCO3) and ammonia. The Solvay process involves saturating a concentrated brine solution with ammonia to form ammonium salts and then with carbon dioxide (made by burning lime). This produces ammonium bicarbonate which reacts with the brine to form ammonium chloride and sodium carbonate. This material, in the presence of excess carbon dioxide, is converted to sodium bicarbonate which precipitates out of the solution and can easily be decomposed to soda ash by heating. The resulting carbon dioxide can be recycled and the ammonium chloride treated to recover reusable ammonia.

At present, soda ash production in China amounts to a total of 15 million tons annually. However, it is estimated that by 2010, the entire market for soda ash made in China could be as large as 20 million tons per year. Shandong Haihua Group, Weifang, in the province of Shandong in East China, is the world's largest synthetic soda producer with an output of 2.4 million tons of soda ash per year. Haihua has adopted Siemens PCS7 DCS in its new plant that has a capacity of 1.2 million tons of soda ash per year. The process control system provides an integrated solution for controlling the processes in the new plant as well as has ability to monitor both field instrumentation and power supply components, support production information management system.

The carbonation process is the most important operation unit in ammonia soda ash plant. The temperature profile of the carbonation tower is carefully controlled to give sodium bicarbonate crystals of the required size and to maximize bicarbonate yield. Considerable improvements in operation efficiency and significant reduction in production cost can be achieved if the carbonation towers are operated in an optimal way by process control. Conventionally, the carbonation towers are controlled by multi-loop PID controllers which are usually decoupled to avoid multivariable interactions but these controllers generally have drawbacks, such as input/output pairing problems and hard tuning work. Moreover, the control schemes are only based on feedback control strategies, lack model prediction, constraint resolution and multivariable coordination, the control actions have to always follow the errors that

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Corresponding Author: Jin Xiaoming, Institute of Cyber-Systems and Control, Zhejiang University, 310027, Hangzhou, China happened on controlled variables. For carbonation towers characterized by strong coupling among process variables, severe disturbance and process nonlinearity, a predictive control is more suitable in this case.

Up to present, Model Predictive Control (MPC) has become the most widely used multivariable control algorithm in chemical process industries and other areas (Rawlings, 2000; Qin and Badgwell, 2003; Dufour and Toure, 2004; Bezzo *et al.*, 2005; Hou, 1942). Differing from many other multivariable control strategies, MPC is conceived primarily from the industry needs. Besides easy tuning and no variables pairing problems, MPC demonstrates remarkable features when applied to the problems with: (1) A large number of manipulated and controlled variables, (2) Constraints imposed on both the manipulated and controlled variables and (3) Difficult processes such as processes with large time delays, time-varying characteristics and nonlinearities, etc.

This study presents an application of model predictive control in carbonation towers. The rest of the study is organized as follows: Process description of carbonation towers in Section 2. After a brief description of MPC scheme in Section 3, an industrial application with constrained MPC scheme in an ammonia soda ash plant is illustrated in Section 4. Conclusions are given in Section 5.

PROCESS DESCRIPTION

Solvay Process: The flow diagram for the production of ammonia-soda by Solvay process is presented in Fig. 1.

The first step in the ammonia-soda process is brine preparation. Sodium chloride solutions are usually obtained by solution mining of salt deposits which gives a raw, nearly saturated brine containing a low concentration of impurities such as magnesium and calcium salts. The brine has to be purified to prevent the scaling of processing equipment and contamination of the product. To purify it, the brine is treated with lime milk to precipitate magnesium and with soda ash to precipitate calcium.

The brine needed for the soda process is sent to the ammonia absorbers. In the absorption tower the strong brine is saturated with ammonia gas. The ammoniated brine is pumped into the carbonator tower, in which rising CO_2 (compressed lime kiln gas and bicarbonate calciner gas) meets falling ammoniacal brine. A bicarbonate sediment, a solution of unprocessed N_aCl and NH_4Cl is obtained from the carbonation process. The slurry of N_aHCO_3 which forms, is fed into vacuum filters or centrifuges which separate the crystals from the filter liquid. The filter cake (crude bicarbonate) is calcined to carbon dioxide and sodium carbonate, called soda ash.

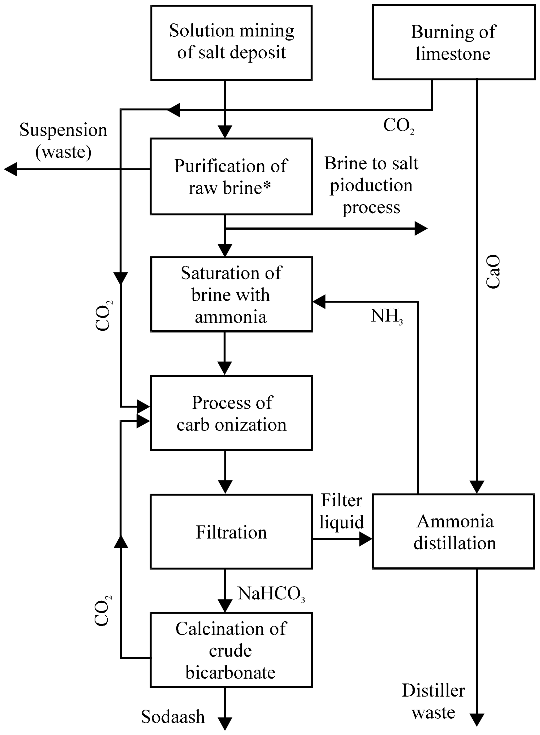

Fig. 1: Flow diagram for the production of soda by the solvay process

Main chemical reaction: The Solvay process relative to the production of soda ash could be summarized by the theoretical global equation involving the two main components: Sodium chloride and calcium carbonate:

$$2N_aCl+C_aCO_3 \rightarrow N_{a2}CO_3+C_aCl_2$$

In practice this direct way is not possible and it needs the participation of other substances and many different process steps to get the final product: soda ash.

First reactions occur in salt solution (brine). First of all, ammonia is absorbed (1) And then, the ammoniated brine is reacted with carbon dioxide to form successive intermediate compounds: Ammonium carbonate, (2) Then ammonium bicarbonate, (3). By continuing carbon dioxide injection and cooling the solution, precipitation of sodium bicarbonate is achieved and ammonium chloride is formed and (4). Chemical reactions relative to different steps of the process are written below:

$$N_aCl+H_2O+NH_3 \leftrightarrow N_aCl+NH_4OH \quad (1)$$

$$2NH_4OH+CO_2 \leftrightarrow (NH_4)_2\ CO_3+H_2O \quad (2)$$

$$(NH_4)_2CO_3+CO_2+H_2O \leftrightarrow 2NH_4HCO_3 \quad (3)$$

$$2NH_4HCO_3+2N_aCl \leftrightarrow 2N_aHCO_3\downarrow+2NH_4Cl \quad (4)$$

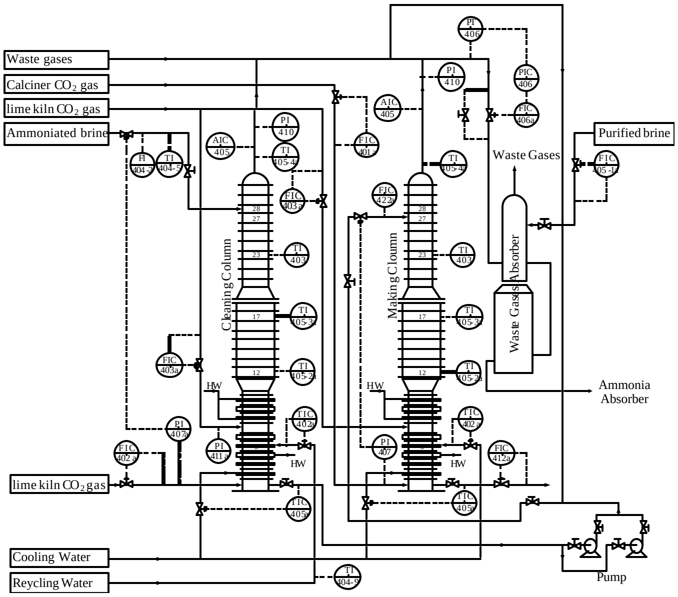

Fig. 2: Process diagram of the carbonation towers with two working patterns

Sodium bicarbonate crystals are separated from the mother liquor by filtration, then sodium bicarbonate is decomposed thermally into sodium carbonate, water and carbon dioxide 5.

$$2N_aHCO_3 \rightarrow N_{a2}CO_3+H_2O\uparrow+CO_2\uparrow \qquad (5)$$

CO_2 is recovered In the carbonation step (see equations 2 and 3 above). CO_2 recovery cycle is shown in Fig. 1.

Mother liquor is treated to recover ammonia. The ammonium chloride filtrate, (4) Is reacted with milk of lime (6) Followed by steam stripping to recover free gaseous ammonia:

$$2NH_4Cl+C_a\,(OH)_2\rightarrow C_aCl_2+2NH_3\uparrow+2H_2O \qquad (6)$$

NH3 is recycled to the absorption step (Eq. 1 above). Ammonia recovery cycle is shown in Fig. 1.

Carbon dioxide and calcium hydroxide originate from limestone calcination (7) Followed by calcium oxide hydration (8).

$$C_aCO_3 \rightarrow C_aO+CO_2\uparrow \qquad (7)$$

$$C_aO+H_2O \rightarrow C_a\,(OH)_2 \qquad (8)$$

Brine has to be treated before the input in the process to remove impurities: Calcium and magnesium. If not removed they would react with alkali and carbon dioxide to produce insoluble salts contributing to scale formation inside equipment. Brine purification reactions are described in the following equations:

$$C_{a2}++CO_{3\,2}-\rightarrow C_aCO_3\downarrow \qquad (9)$$

$$Mg_2++2OH-\rightarrow Mg\,(OH)_2\downarrow \qquad (10)$$

Carbonation system: The ammoniated brine from the absorber coolers is pumped to the top of one tower in a block of towers used to carbonate with carbon dioxide to precipitate bicarbonate. This tower which has been fouled or partially plugged with sodium bicarbonate after several days of crystallization is referred to as a “cleaning” tower. Lime kiln gas enters the bottom of the cleaning tower and bubbles up through the solution to absorb most of the carbon dioxide. The concentration of carbon dioxide in the liquor is kept below the precipitation concentration. Relatively little cooling is required. The scale is dissolved off the cooling surfaces of the cleaning tower by the fresh ammoniated brine, assisted by gas agitation. The liquor leaving this tower is fed in parallel to the top of the remaining towers in to block. A stronger carbon dioxide gas made up of a mixture of kiln gas and bicarbonate calciner gas is fed to these crystallizing or "making" towers and bubbles up through the solution. This process precipitates sodium bicarbonate and is accompanied by the evolution of considerable heat which must be removed to improve yield. Crystals formed during the carbonation step gradually foul the heat-exchange surfaces and thus a crystallizing tower must alternately be the "cleaning" tower. The gases which are predominantly nitrogen but also contain carbon dioxide and ammonia, are vented from the cleaning and making towers and collected of recycling to the absorber.

The carbonation tower is not only a multiphase reactor but also a multistage crystallizer. The complex processes included chemical absorption, reactive precipitation, multiphase flow, heat and mass transfer and other physical-chemical effects are taken place in the tower. There are more than ten operating variables on the performance of the industrial carbonation tower. The temperature profile along with the height of the carbonation tower should be carefully controlled to ensure sodium bicarbonate crystals growing to the required size and to maximize soda ash yield. Consequently, the towers need to be maintained close to optimal operating conditions lay at some constraints.

Due to its complexities and difficulties, the control design of carbonation system has attracted much attention. First, a large number of variables involved have severe interactions among them which means that when one output or controlled variable is regulated with one input or manipulated variable, other controlled variables will be unavoidably influenced in an undesired fashion. Sec, the existence of substantial coupling of manipulated variables, severe disturbance, non-stationary behavior and process nonlinearity can also cause undesirable effects on process behaviors. However, regulatory controls of carbonation tower are difficult to achieve favorable control performance all the time for moving the tower to its optimal operating point and rejecting disturbances on the controlled variables in the tower. Therefore, for the control of carbonation tower, especially several blocks of towers affected by many constraints, Model Predictive Control (MPC) can be used to improve control performance characterized by a reduction in the variability of the controlled variables through information gathering, process analysis and constrained multivariable optimization.

MPC CONTROL ALGORITHMS

MPC is a control strategy which predicts the future behavior of the controlled process in a control envelope from the past moves of Manipulated Variables (MVs) with using the dynamic models of the Controlled Varaables (CVs) versus MVs and determines the future moves of MVs in order that CVs will match the target values as close as possible without any violations in the operating constraints in each control cycle. Model Algorithmic Control (MAC) is adopted to realize the overall control of the carbonation towers. The relationship between CVs and MVs is given in impulse response form that can be achieved by experimental test and process identification:

$$y_m(k) = \sum_{j=1}^{N} \hat{h}_j u(k-j) \tag{11}$$

Where, $\hat{h}_j$ is the coefficients of impulse response, y is C, u is MV and N is number of impulse. The subscript m denotes model output. Model vector h = $[\hat{h}_1 \cdots \hat{h}_N]^T$ is often saved in host computer and names internal model.

The closed-loop predictive model is obtained in terms of Eq. 11 as follows:

$$\begin{aligned} y_p(k+i) &= y_m(k+i) + [y(k) - y_m(k)] \\ &= y(k) + [y_m(k+i) - y_m(k)] \end{aligned} \tag{11}$$

$$= y(k) + \sum_{j=1}^{N} \hat{h}_j \begin{bmatrix} \Delta u(k+i-j) + \Delta u(k+i-j-1) \\ + \cdots + \Delta u(k+2-j) + \Delta u(k+1-j) \end{bmatrix} \tag{12}$$

Where, the subscript m denotes model predictive output, y (k) is current process output, I = 1, 2, ..., p.

The reference trajectory that is used to smooth expected output from y (k) to setpoint y_{sp} adopts first order exponential form in MAC as follows:

$$\begin{cases} y_r(k+1) = \alpha^i y(k) + (1-\alpha^i) y_{sp} \qquad i = 1, 2, \cdots, P \\ y_r(k) = y(k) \end{cases} \tag{13}$$

Where, α = esp (-T/π), T is sample time and π is constant time of reference trajectory. To meet the above control goals, the objective function can be formilated as follows:

$$\begin{aligned} J = &\left[y_p(k+1) - y_r(k+1)\right]^T Q \left[y_p(k+1) - y_r(k+1)\right] \\ &+ u_2^T(k) R u_2(k) \end{aligned} \tag{14}$$

Where:

$$Q = \text{diag}\left[q_1, q_2, \cdots, q_P\right]$$

$$R = \text{diag}\left[r_1, r_2, \cdots, r_M\right]$$

$$y_r(k+1) = \left[y_r(k+1), y_r(k+2), \cdots, y_r(k+P)\right]^T$$

MPC scheme is implemented in a moving horizon framework. At any sampling instant, the optimization problem is formulated over the prediction horizon and a future manipulated variable trajectory is calculated that minimizes the objective function satisfying all the constraints. Only the first move is applied to the plant and this step is repeated for next sampling instant.

INDUSTRIAL APPLICATION

The system based on MPC strategy was put into operation in the new soda plant of Shandong Haihua Group in 2005 and is now still running after three years. The connection between the MPC system of the carbonation towers and PCS 7 DCS system is shown in Fig. 3. The advanced multivariable robust predictive control software APC-Adcon that consists of the components of modeling, controller design, simulation, configuration and online application is used to the to three subsystems according to the blocks of carbonation system in the plant. Each subsystem is relatively independent with the others and mainly takes charge one block. The independent variables (MVs and disturbance variables, namely DVs) and dependent variables (Cvs) for the "making" tower and the "cleaning" tower are listed in Table 1 and 2.

After the MPC controller was tuned, it was tested on-line for three months. The comparison of the control performance before and after the MPC implementation is summarized. The comparison of 17th temperature and pressure of one "making" tower is is shown in Fig. 4 and Fig. 5.

The MPC control system is superior to human supervisory control in follow aspects:

- The skill of most high experienced operator has been implementation
- Operation and compensation is executed at fairly frequent intervals. In case of a skilled operator, operation frequency is about 15 min, while, in case of MPC system, it is 1 min
- Operator control manipulates the process variables in sequence. Nevertheless, the MPC control can manage several process variables in parallel

After the implementation of the MPC system, the deviation of the main process variables became one half of that before implementation. As a result, The over economical merit from this implementation is

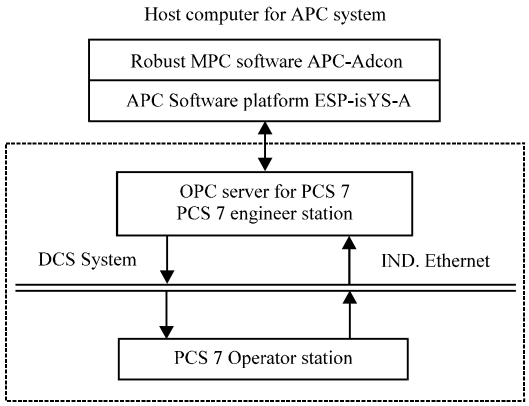

Fig. 3: Connection between the MPC system and PCS7 DCS

Table 1: Configuration for "making" tower MPC system

Manipulated variables (MVs)		Controlled variables (CVs)		Disturbance variables (Dvs)	
Tags	Describing	Tags	Describing	Tags	Describing
FIC-422.SV	Flowrate of ammoniated brine with CO_2	PI-407.PV	Tower bottom pressure	PT-406.PV	Waste gases pressure
FIC-403.SV	Lime kiln CO_2 gas flowrate	TI-405-2.PV	The twelfth layer temperature	TI-404-9.PV	Recyclingwater temperature
FIC-401.SV	Calciner CO_2 gas flowrate	TI-405-3.PV	The seventeenth layer temperature	TI-404-8.PV	Cooling water temperature
FIC-412.SV	Suspension of crystals flowrate	TI-403.PV	The twenty-third layer temperature		
TIC-405.OP	Cooling water flowrate	TIC-402.PV	The fifth layer temperature		
TIC-402.OP	Recycling water flowrate	TIC-405.PV	Suspension of crystals temperature		

Table 2: Configuration for "cleaning" tower MPC system

Manipulated variables (MVs)		Controlled variables (CVs)		Disturbance variables (Dvs)	
Tags	Describing	Tags	Describing	Tags	Describing
FIC-422.SV	Flowrate of ammoniated brine	PI-407.PV	Tower bottom pressure	PT-406.PV	Waste gases pressure
FIC-403.SV	Lime kiln CO_2 gas flowrate	TIC-402.PV	The fifth layer temperature	TI-404-9.PV	Recycling water temperature
TIC-405.OP	Cooling water flowrate	AI-401.PV	Concentration of ammoniated brine with CO_2	TI-404-8.PV	Cooling water temperature
TIC-402.OP	Recycling water flowrate	TI-403.PV	Temperature of ammoniated brine with CO_2	TI-422.SV	Ammoniated brine temperature

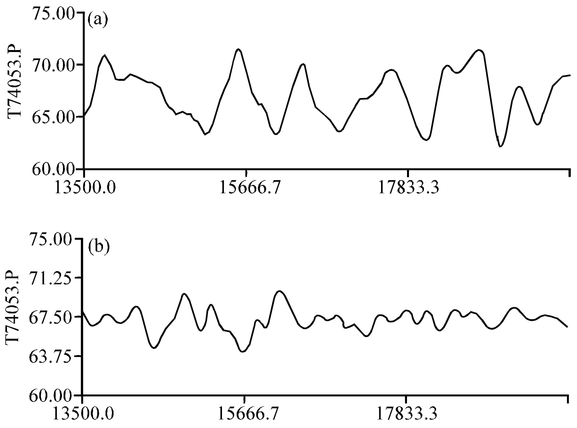

Fig. 4(a-b): Temperature of a tower before MPC implementation, temperature of a tower after MPC implementation, Comparison of temperature control performance under MPC and PID

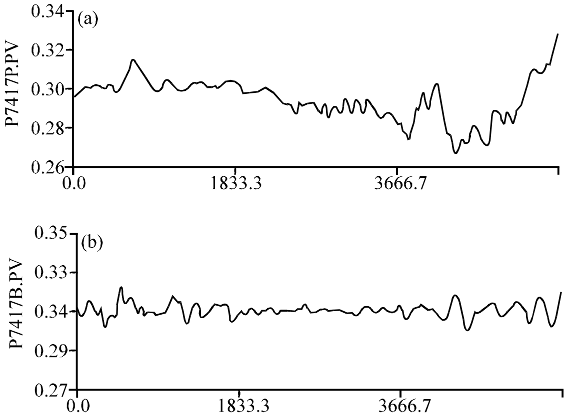

Fig. 5(a-b): Pressure of a tower before MPC implementation, Pressure of a tower after MPC implementation, comparison of pressure control performance under MPC and PID

approximately over six million yuan by increasing the production of soda ash, improving product purity and minimizing operating cost.

CONCLUSION

This study introduces industrial application via a commercial software of MPC for carbonation towers in a soda plant which consists of fifteen carbonation towers, A MPC system in which is constructed of controlled variables, manipulated variables and disturbance variables is developed to deal with the constrained multivariable control problem on-line of the carbonation towers. Industrial application results show that the MPC software can maintain the best operation for a long time and realize ultimate operating potential of the carbonation systems by reducing the consumption of material, improving product quality and minimizing operating cost.

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