Multivariable Predictive Control and its Application on the Solvent Dehydration Tower

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Abstract: Multivariable Predictive Control strategies with the help of software package of *APC-Hiecon* are applied to control a Solvent Dehydration Tower (SDT). A controller is designed to help solve the problems such as fluctuation of the feeding, the cross effects and the liquid flooding in the running process of the tower. The stability of SDT is improved evidently after the application of the controller. The actual control result shows a visible reduction of the cost of HAc and a subsequent distinct economical profit.

Keywords: Advanced Process Control, Multivariable Predictive Control, Solvent Dehydration Tower, *APC-Hiecon*

INTRODUCTION

Model-based predictive control (MPC) has been developing fast in both its academic research and industrial application. The three characteristics of MPC are predictive model, receding horizon control and feedback correction. In the process industries, one of the most attractive features of MPC is its ability to deal with constraints and cross effects in multivariable control problems. Some commercial software packages based on the principle of the predictive control have been developed (Adersa Inc. Report, 1991a, 1993b, 1995c). The application of these software packages has already had lots of instances all over the world (Richalet, *et al.*, 1978; Richalet, 1993). In this paper, the application of MPC strategies on the Solvent Dehydration Tower (SDT), with the help of the software packet of APC-Hiecon, is introduced. The process parameters are unstable under the conventional PID control. In order to improve the control performance, a multivariable predictive controller was designed by using the software package of *APC-Hiecon* to control the process. *APC-Hiecon* provides the general functions of model-based predictive control, i.e. the cross effects and constraints are inherently considered in the controller and the measurable disturbances are effectively compensated by feed-forward action. At the same time, in order to restrain the liquid flooding, a flooding detector is introduced into the controller. Thus, the control structures are switched automatically via the indication of the flooding detector. Considering the specific condition of the tower, the inner-reflux flow rate control and the pressure compensated temperature control are also introduced into the control system. The control performance after the application of APC-Hiecon is very satisfying.

2. TECHNICAL FEATURES AND FORMER CONTROL STATUS OF THE SDT

2.1 Technical Features of the SDT

Producing purified terephthalic acid (PTA), according to the Amoco Patent, PX, HAc, Catalyzer(Co-Mn), assist Catalyzer(HBr) and air are fed into Oxygenating Reactor continuously. Under certain pressure and temperature, PX is mostly oxygenated into CTA first, then after crystallization, it is purified to eliminate 4-CBA by adding hydrogen, finally the PTA(>99.9%) is obtained. So the PTA device can be divided into two parts --- Oxygenation and Purification. During the production of PTA, there is 2mol H_2O produced while 1mol TA was obtained. The H_2O produced will dilute HAc Solvent, which can be reused only by dehydration through a solvent dehydration tower. The Solvent Dehydration Tower is an important device in the Oxygenation part. It can be regarded as a binary distillation column to separate the H_2O and HAc. The H_2O contained in the solvent at the bottom of tower should not be over 8% as required. Otherwise, the redundant water will affect the temperature in the reactor. However, the HAc contained in the water at the top of tower should be as little as possible, so as to reduce the cost of HAc, protect the environment and decrease the rust of equipment.

In the Chemical Factory of a certain Chemical Fiber Company, the main problems of SDT lie in the following three aspects. First, the operation flexibility of SDT is limited when the load is increased to 130% of its original design. Second, the separating efficiency cannot meet the originally designed index under the high load condition. Third, under traditional control, when the reflux flow rate is above 42t/h, liquid flooding easily takes place. The chief cause for these problems is that the capacity of the SDT could not fit the enlarged load. The situation was not improved much even after most part of the tower had been changed from sieve plate to stuffing. This leads to the result that the SDT becomes very sensitive to disturbances. The SDT has four parts of fed-in materials: two of them are vapor and the other two are liquid. Among them, only the liquid (FI408, see Fig. 1) drawn out from the reactor is measurable. This part occupies nearly 40% of the feed rate. The other 60% of the feed rate is unmeasurable and fluctuates frequently.

2.2 Former Control Status of the SDT

In the former technical design of the SDT, the control strategies are to adjust the concentration of H_2O through steam flow rate and to adjust the concentration of HAc through reflux flow rate. The traditional control loops are as follows:

Double cascade control system formed by conductivity CIC402 at the bottom, the temperature TIC424 at the bottom and the steam flow rate FIC424.

Cascade control system formed by conductivity CIC401 at the top and reflux flow rate FIC421.

However, from the very beginning, the above control systems have not been adopted to achieve the quality control of both the bottom and top part of the tower simultaneously. For some reason, only TIC424-FIC424 cascade control can be applied. Therefore, only the bottom quality of SDT is controlled in the former control system. Thus, the conductivity CIC401 and CIC402 are only reference index.

The operators usually adjust the set points of bottom temperature TIC424 and reflux flow rate FIC421 to manipulate the tower. Due to the long time-delay, the long time response and the strong cross effects, the temperature and pressure trends in the SDT are uneven under conventional PID control. So the production qualities are often unstable for the high diversity.

At the same time, the correlation between pressure and temperature often confuses the relation between the bottom component and bottom temperature.

In addition, the unexpected changes of weather like rainstorm affects the SDT greatly, when the reflux temperature TI446 will have a big fluctuation.

The worst thing to the SDT is that it gets easily into the liquid flooding mode. The symptom of flooding is that the differential pressure of the tower PDI422 increases exponentially. In consequence, the bottom temperature increases rapidly while the bottom liquid level decreases speedily.

The schematic flow chart is depicted in Fig. 1.

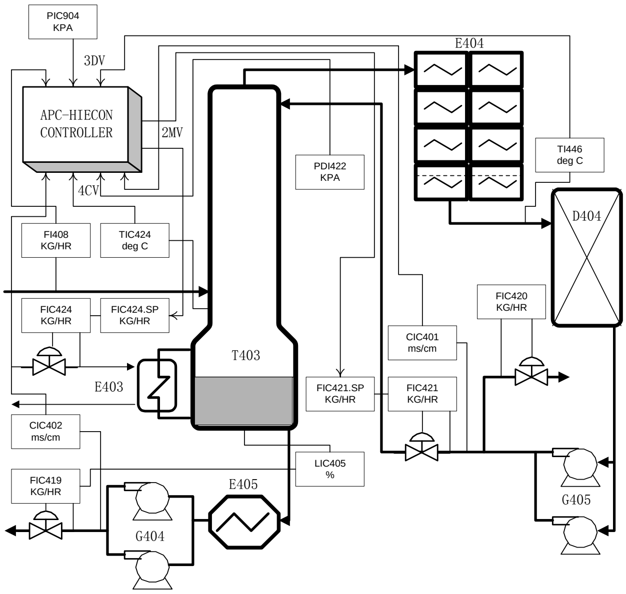


Fig. 1 Flow chart of the SDT

3. ADVANCED PROCESS CONTROL STRATEGY OF THE SDT

To solve the problems described in the above section, we choose the software packet APC-Hiecon which is based on the strategies of MPC. MPC has become the main approach in the advanced industrial process control. It uses the following three kinds of variables:

CV: Controlled Variable

MV: Manipulate Variable

DV: Measured Disturbance Variable

The key to a successful application of MPC depends on the selection of CV, MV and DV and the accuracy of the process model. In the *APC-Hiecon* Controller designed for the SDT, the CVs, MVs and DVs are listed in Table 1.

Table 1 *APC-Hiecon* Controller Variables List

CVs		MVs		DVs	
CV 1	CIC401.PV	MV 1	FIC421.SP	DV 1	FI408.PV
CV 2	CIC402.PV	MV 2	FIC424.SP	DV 2	TI446.PV
CV 3	PDI422.PV			DV 3	PIC904.PV
CV 4	TIC424.PV				

3.1 Process Model of the SDT

The process controller design relies on the availability, or development, of a process model that describes the process dynamics with sufficient accuracy to enable design of a controller to achieve the required closed loop performance. To identify the process model, MVs need to be changed step by step during the response test. In this project, step changes of the set points of FIC421 and FIC424 are made one by one for several times. The special patterns of the step changes are shown in Fig. 2. (TR means the time for a CV to reach a steady state.)

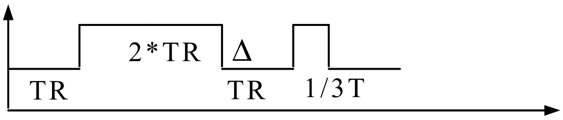


Fig. 2 Test Signal Pattern

For the DVs, since they can not be changed as the MVs, the only way to identify the process model is to handle long term normal operation data. The DVs are likely to have a lot of changes during a long time period.

The test data of MVs and DVs are dealt with by the identification tool of the APC-Hiecon. The process model was obtained easily in this way. The process dynamics is represented by the impulse response models which describe the relationship between CVs and MVs, DVs. Here the almost equivalent Laplus transfer functions for the models are listed in Table 2.

Table 2 Transfer Functions List

	FIC421	FIC424
CIC401	$-0.012* e^{-3s}/(1+25s)$	$0.01* e^{-3.5s}/(1+12s)$
CIC402	$0.0036* e^{-4s}/(1+20s)$	$-0.004* e^{-0.5s}/(1+7s)$
PDI422	$0.002* e^{-0.5s}/(1+7s)$	$0.003* e^{-0.5s}/(1+3s)$
TIC424	$-0.0014* e^{-0.5s}/(1+8s)$	$0.002* e^{-0.5s}/(1+4s)$

3.2 Controller design of the SDT

Using the design tool of APC-Hiecon, a MPC controller is naturally designed from the previously identified process model. The main tasks during the design work are to translate the control objects of the SDT to special forms of the software packet and to tune the controller elaborately. The features of the controller lie in the following three aspects.

Switch between basic controller and flooding controller. The structures of basic controller and flooding controller are shown in Table 3 and 4. The basic controller is designed to keep the bottom temperature TIC424 around the set point and minimize the top conductivity CIC401 while the other parameters, CIC402 and PDI422, are rested in the reasonable scope. There is another special controller to handle the liquid flooding. The primary aim in the flooding controller is to draw the differential pressure PDI422 back to the ideal scope. A flooding detector, which is detecting the PDI422, is embedded into the program. Thus, the control structures are switched automatically via the indication of the flooding detector.

Table 3 Basic Controller Structure

CVs		MVs	
CV1	CIC401.PV (Minimization)	MV1	FIC421.SP (Position and Speed Constraints)
CV2	CIC402.PV (Max Constraint)	MV2	FIC424.SP (Position and Speed Constraints)
CV3	PDI422.PV (Max Constraint)		
CV4	TIC424.PV (Setpoint Control)		

Table 4 Flooding Controller Structure

CVs		MVs	
CV1	CIC401.PV (Without Control)	MV1	FIC421.SP (Position and Speed Constraints)
CV2	CIC402.PV (Without Control)	MV2	FIC424.SP (Position and Speed Constraints)
CV3	PDI422.PV (Setpoint Control)		
CV4	TIC424.PV (Without Control)		

Inner-reflux flow rate control. It is the inner-reflux flow rate that really influence the separating efficiency of the SDT rather than the outer-reflux flow rate. In order to overcome the effect of the fluctuation of the reflux temperature, the inner-reflux flow rate conversion is introduced into the system. The APC-Hiecon controller calculates the set point of the inner-reflux flow rate. Then the set point of the inner-reflux flow rate is transferred to the set point of the actual reflux flow rate. The conversion equation is listed as the follows:

$$\mathrm{FIC421.SP}=\mathrm{FIC421.M}*(1+\lambda(T_0-\mathrm{TI446.PV})) \quad (1)$$

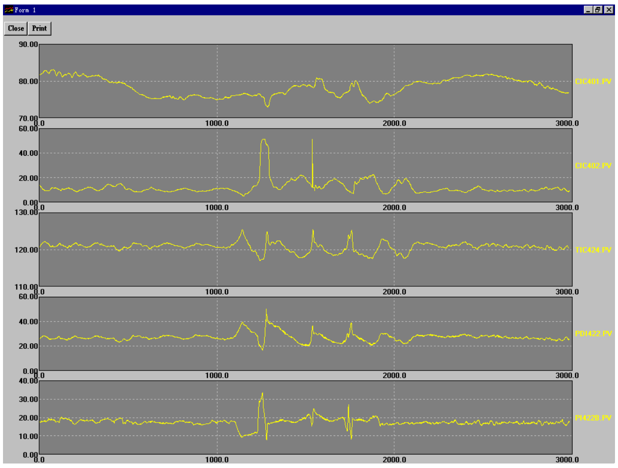
FIC421.M: Set point of inner-reflux flow rate

T_0: Boiling point of the reflux flow

λ: Coefficient

Pressure compensated temperature control. The top pressure PI422B was badly controlled because of the problem of a valve in SDT. The correlation between bottom pressure and bottom temperature often confuses the relation between the bottom component and bottom temperature. Consequently, it is necessary to compensate the bottom temperature by the pressure.

Fig. 3 Time Trends Before the Application



The compensation equation is as follows:

$$\mathrm{TIC424.SP}=T_O+\gamma(P_O-\mathrm{PI422A.PV}) \quad (2)$$

TIC424.SP: Set point of the bottom temperature

PI422A.PV: Bottom pressure

T_O: Norm temperature

P_O: Norm pressure

γ: Coefficient

4. PERFORMANCE OF APC-HIECON

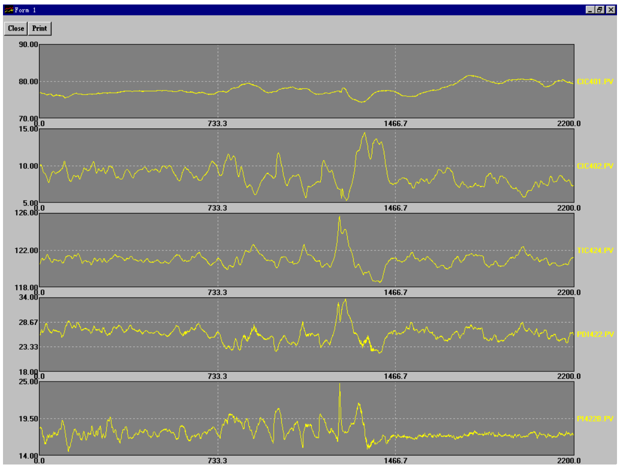
After the application of *APC-Hiecon* on the SDT, the frequency of liquid flooding is greatly reduced and the average concentration of HAc at the top of the tower is decreased from 3.0% to 2.6%.

The time trends of the key variables before the application are shown in Fig. 3 and those after the application are shown in Fig. 4. (The scales of two figures are different. The scale of Fig. 4 is smaller.) There are five curves in both of the two figures, which represent the time trends of five different variables (i.e. CIC401, CIC402, TIC424, PDI422, PI422B). It can be drawn from the figures that the standard deviation of CVs is reduced greatly after the application.

Under the traditional PID control, the operators have to deal with the liquid flooding manually. As shown in the framed part of the Fig. 3, during the flooding, the time recovering to the steady state is very long and the amplitude of the trends is very high. Meanwhile, as shown in the framed part of Fig. 4, the APC-Hiecon controller can handle the liquid flooding automatically.

The flooding has been restrained quickly and the amplitude of the trends is comparatively much lower.

Fig.4 Time Trends After the Application



5. CONCLUSION

With the successful application of the APC-Hiecon, the SDT could steadily run at a point near the flooding limit. It shows the advantage of the model-based predictive control software packet, the control performance is improved visibly. The reduction of the cost of HAc is very satisfying and a distinct economical profit is obtained. Meanwhile, it brings other good effects like protecting the environment and decreasing the rust of equipment.